Renewable and Sustainable Energy Reviews 40 (2014) 515–541

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Integrated HVAC and DHW production systems for Zero Energy Buildings

Enrico Fabrizio [a,*], Federico Seguro [b], Marco Filippi [b]

[a] DISAFA, Università degli Studi di Torino, Largo Paolo Braccini 2, 10095 Grugliasco (TO), Italy
[b] DENERG, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

ARTICLE INFO

Article history:
Received 17 February 2014
Received in revised form
1 July 2014
Accepted 28 July 2014

Keywords:
Multi-energy systems design
Renewable energy
Residential buildings
Building services
ZEB (Zero Energy Buildings)

ABSTRACT

The integration of different energy sources to cover with the maximum efficiency the building energy demand is one of the principles for achieving the target of the nearly net Zero Energy Buildings (*nNZEBs*), as defined by the EPBD recast (2010/31/EU). Following this principle, there has been a shift from a conventional mono-carrier/mono-converter based logic (one energy source is used in one energy converter to meet each load) to a multi-carrier/multi-converter logic (a mix of energy sources feeds two or more energy converters to cover the energy loads).

This paper reviews the technology, performance and the parameters of the latest multi-energy systems for residential ZEB on the market. The scope of the work is to provide the necessary information in order to design and operate integrated HVAC and domestic hot water (DHW) production systems. After characterising the building energy demand (forms of energy, thermal levels, peak loads and so on), the review focuses on integrated energy systems providing: heating energy for space heating and DHW production; heating and cooling energy for air conditioning and DHW production; heating energy for space heating, DHW production and electricity; heating and cooling energy for air conditioning, DHW production and mechanical ventilation. A schematic of each technology and a table contrasting the strengths, advantages, weaknesses and drawbacks of the various technologies are also provided.

Contents

Abbreviations: CHP, combined heat and power; COP, coefficient of performance; DHW, domestic hot water; DX, direct expansion; EER, energy efficiency ratio; ESEER, European seasonal energy efficiency ratio; EU, European Union; GAHP, gas absorption heat pump; GEHP, gas engine heat pump; GUE, gas utilisation efficiency; MV, mechanical ventilation; nNZEB, nearly net Zero Energy Building; PCM, phase change material; PER, primary energy ratio; PV, photovoltaic; SAHP, solar assisted heat pump; SCOP, seasonal coefficient of performance; SPI, specific power input; T_{in}, source side temperature; T_{out}, use side temperature; T_{ws}, water source temperature; VRF, variable refrigerant flow; VRV, variable refrigerant volume; ΔT, delta temperature difference

* Corresponding author. Tel.: +39 011 6705525; fax: +39 011 6705516.
E-mail address: enrico.fabrizio@unito.it (E. Fabrizio).

http://dx.doi.org/10.1016/j.rser.2014.07.193
1364-0321/

1. Introduction

Regulation of buildings energy consumption is strategic for the European Union (EU) in order to reduce greenhouse gas emissions and global temperature rise. To this regard, EU launched the recast of the Energy Performance of Buildings Directive (2010/31/EU), requiring Member States to implement in the near future nearly net Zero Energy Buildings (nNZEBs), high energy performance buildings with a limited energy demand and a significant coverage by renewable energy sources [1]. Basically, the nNZEB's energy consumption is reduced as much as possible in order to be covered by energy systems fed by renewable sources.

The focus on the exploitation of renewable sources with a view to match the building energy demand with a local energy supply, is leading increasing attention towards multi-energy systems in buildings, also known as “hybrid” or “integrated” systems [2,3]. Instead of relying on one-source/one-product systems – one energy source used in one energy conversion system to meet each load – multi-energy systems integrate a mix of different energy sources (at least one of which renewable) to feed two or more energy converters.

As the efficiency of specific building components and systems has been increasing due to technological innovation, potential improvements have indeed become limited, while further energy performance upgrading appear rather to lie in the integration of different technologies (IEA-ECBCS Annex 44, 2010). Hybrid solutions, transcending the respective limits characteristics of stand-alone energy systems [4] allow next steps in energy savings to be reached.

This integrated perspective can be implemented in different ways. In literature multi-energy systems have been studied in relation to the exploitation of solar energy for heating and cooling [5–7]; fuel cell stack [8] and hydrogen storages [9–11] fed by wind energy; combined heat and power (CHP) systems integrated with absorption chillers and desiccant cooling [12]; geothermal heat pumps coupled to the solar thermal system [13]; photovoltaic, thermal and wind energy coupled to cogeneration systems [14]. There is a lack, however, on the design and operation of small multi-energy systems for buildings.

This paper presents an overview of the latest integrated systems available for the residential market – discussing the strengths, peculiarities and possible weaknesses – in order to orient stakeholders to consciously choose the best alternative among the many different options that exist. All these options are characterized by the fact that they can be used in residential housing units, particularly single-family houses (from 50 to 200 m^2 of heated surface area). Some systems may be suitable for larger residential housing types (e.g., blocks of apartments) and are included in the review but the main focus is the single-family house level. This is also the reason why systems of interlinked buildings (micro grids and district heating solutions) were not taken into account. The scope of the paper is to provide the information on what types of integrated systems may be used, what are the layouts of such systems, what are the most cutting-edge and promising technologies in this field. Then, for each case study the necessary calculations and feasibility study in order to size the system should be done. This article may provide, at least at the early stages, the necessary information to proceed in this direction.

There is a variety of energy uses in a residential building. Integrated energy systems reviewed in this paper consider the following energy uses:

- space heating;
- domestic hot water (DHW) production;
- space cooling;
- mechanical ventilation and air handling (heat recovery, heating, cooling and dehumidification);
- electric lighting; and
- plug loads.

The various building energy uses are basically covered by electricity, heating and cooling energy. According to the thermal level required at the user side or at the production side, heating and cooling energy can be further split up into

- heating energy for high-temperature space heating, ranging from 55 °C to 80 °C;
- heating energy for low-temperature space heating, from 35 °C to 50 °C (radiant heating);
- heating energy for DHW, from 40 °C to 65 °C;
- cooling energy for space cooling, from 7 °C to 19 °C;
- cooling energy for air dehumidification, below 12 °C.

A nNZEB experiences a reduction of both the heating design load and the heating energy demand for space heating, while the heating design load for DHW production is higher (up to more than two times) than the heating design load for space heating and the DHW energy demand is concentrated in time and constant throughout the year. Still, in a nNZEB there is the need to recover the waste heat from ventilation.

Whereas the main thermal, cooling and electricity loads in commercial buildings such as offices, are usually separately met by single energy converters, a growing interest is currently being addressed to integrated energy systems in the residential sector. In fact, the limited design capacities, the need to minimise construction costs and simplify maintenance and operation, attract producers towards integrated solutions for residential NZEB.

The rationale behind the classification done in the present review is not based on the energy carriers or on the energy system

adopted, but on the energy use. Integrated systems can provide the following uses:

a) space heating and DHW production;
b) space heating, space cooling and DHW production;
c) space heating, DHW production and electricity; and
d) space heating, space cooling, DHW production and mechanical ventilation.

Integrated systems for trigeneration are not considered in this paper since less common in the residential building sector.

Fig. 1 introduces most of the integrated systems under review in this work according to the energy sources exploited (electricity from the utility grid, renewable energy, gas) and the energy uses satisfied (plug loads/lighting, space heating and cooling, DHW, mechanical ventilation). For each technology described below, a colour is placed in correspondence of the energy use covered and the energy source used; a light colour is used when the energy system can be optionally integrated with further energy sources (e.g., solar energy) or for further energy uses (e.g., the heat pump, working in reverse cycle mode to meet the space cooling demand). For example, as shown in Fig. 1, gas condensing boilers coupled with electrical heat pumps for space heating, DHW production and, if necessary, space cooling, allow to run the heat pump when the outside air temperatures are mild whilst, at lower temperatures when the heat pump is no more convenient due to a low coefficient of performance, the condensing boiler is used to cover higher heating loads.

2. Integrated systems for space heating and DHW

2.1. Gas boiler

Wall-mounted gas fired boiler is a well-established system for space heating and DHW production. In particular, the condensing boiler technology appears attractive in virtue of its potential to go beyond 100% efficiencies, measured on the lower heating value, exploiting condensation heat from the fuel combustion. Condensing boilers reach optimal performances with low return temperatures, below the dew point; however, seasonal efficiencies higher than the ones of traditional boilers can be obtained also with high temperature heating equipment such as radiators [15]. In the near future, due to externalities such as global warming, acid rain and urban smog [16], renewable energy sources (e.g., biomass, solar) are expected to replace natural gas as fuel for boilers, and low exergy systems [17] will be exploited to more rationally couple the energy demand with low valued energy supply sources. According to Ozdemin et al. [18], in comparison with biomass-driven energy systems such as wood pellet boilers and wood chip district heating stations, a natural gas condensing boiler has a minor ecological footprint. This is based on the heat supply as well as on lower internal costs (due to energy consumption for space heating and DHW) and external costs (related to airborne pollutants and greenhouse gas emissions), and the technology is defined "almost sustainable" according to a multi criteria decision analysis – mainly due to fuel costs, energy carrier reserves.

Over the last years, a series of advancements on the fuel combustion and on the condensation technique of these boilers were made [15]: condensing boilers with modulation ratios between 25% and 100% of their outputs and small capacity boilers (up to 4 kW) can be installed in buildings with very low energy demand for space heating (providing DHW production by means of a storage tank). A description of the variations in expected performance of this type of boilers, in relation to different loads and uses can be found on [19]. Fig. 2 illustrates an hybrid system combining hot water for space heating and domestic use at a high and low thermal energy level (suitable for radiators and radiant panels), integrated with the solar thermal circuit.

Domestic hot water heating can be provided instantaneously (the DHW heating load is significantly higher that the space heating load) or through an integrated water storage above 50 l size. The size of a water storage connected to the solar circuit depends on whether the solar thermal system serves only the DHW loop or also a space heating loop, and can increase up to 750 l.

2.2. Solid biomass based system

Biomass is an abundant renewable energy source commonly used for thermal energy production. At the building scale, biomass is usually used as wood and various type of systems are now available to cover the heating and DHW energy demand. Moreover, a renewed interest in technologies of wood combustion has been catalysed by their nearly closed C-cycle [20]. Other pollutants formed in the process of wood combustion, including nitrogen oxide and sulphur dioxides, are lower compared to emissions linked to oil or coal combustion [21]. Small scale biomass based HVAC and DHW production systems comprise firewood and pellets fired boilers and pellets room heaters with or without water heat exchanger.

Firewood boilers represent the most diffused renewable-based technology. High performance boilers run with reversed combustion in ceramic combustion chambers which are fed by continuous wood loads [22]. The high temperature uniformly maintained throughout the entire burning process and appropriate oxygen supply rates allow to cut emissions due to incomplete combustion of organic material – reduced also by increasing the residence time of the hot smoke gases – and to optimise the net energy gain from wood burning [22]. The volume of air supplied to the boiler is always higher than the theoretical amount necessary for biomass burning (from 1.3 to 1.4 for solid fuel), however the ratio of air excess should not be oversized to prevent too low combustion temperatures [21]. Integrated heat storage tanks (1–2 m^3 for single-family household) storing thermal energy for a prolonged period of time can be connected to the central heating system [23]. Firewood for residential heating has been increasingly replaced by wood pellets. In contrast to pellets, characterised by well-defined emission factors due to their homogeneous constitution, emissions from firewood boilers are less reliable to be predicted due to unstable burning process and varying fuel quality [24]. Pellets have a moisture content approximately two times lower as compared to firewood [25], which reduces the need for further drying. Other factors encouraging the use of pellets instead of firewood are the limited storage and operation – thanks to the automatic feeding mechanism – a lower fuel requirements and lower GHG average emissions [26]. A typical set-up of a domestic boiler fired with pellets is described in [27]. The pellets collected in a hopper are provided by means of a top-screw feeder to a basket at a rate regulated by the boiler load. An electrical resistance close to the basket aids the combustion process. The primary air is supplied by a fan through small cavities at the bottom of the basket; the secondary air is injected through a vertical tube at the top of the basket. Air flow rates are regulated by the control system and increase according to a pre-defined cleaning schedule to remove the ash formed at the bottom of the basket. Thermal energy from the pellets combustion is transferred to the water circuit through a heat exchanger placed at the top of the combustion chamber. Pollutants emitted by small scale biomass systems include CO and C_xH_y [28], dust [29,30], and SO_x, NO_x [31,32] and are regulated by EN 14785:2006. Emissions and

Fig. 1. Some of the integrated HVAC and DHW production systems under review classified as a function of the service (plug loads & lighting, space heating, etc.) and of the source of energy. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

efficiencies vary according to the operational loads. At reduced load operations, more representative of real life conditions, pollutants increase whilst combustion efficiencies are lower as compared to nominal loads [33]. Gaseous and particulate matter emissions are also linked with fuel type and fuel ash compositions [34] and are higher for boilers operating with pilot flame compared to boilers with electrical ignition.

The growing demand for biomass is raising concerns due to the increasing pressure on woodlands, which may become unsustainable especially in developing countries, mostly reliant on fuelwood to cover energy needs [35]. Accordingly, pellet boilers are increasingly combined with solar thermal systems [36], which can cut pellet consumption and CO emissions respectively by 25% and 44% [37]; an optimisation method for the design of combined solar and pellet heating systems has been proposed in [38].

High energy performance one-floor houses can entirely rely on room heaters (available in a range of sizes from 1.5 to 12 kW) for space heating by radiant and convective heat transfer. Modern pellet stoves integrate a built-in hopper, manually or pneumatically loaded, with pellet feeding driven by a thermostat (one fuel load typically covers 12 and 24 operating hours), a combustion chamber with a forced or induced draft fan, a convection air-blower and an ash drawer [39]; emission requirements are established by EPA. Refractory insulation can be used in the lower parts of the furnace to maintain sufficiently high oxidation temperatures and baffles can be used to increase turbulent gaseous mixing [40]. Stove operation can be regulated remotely through digital timers and dedicated applications. Particular attention should be paid to minimise dust formation to reduce PM and polycyclic aromatic hydrocarbons by installing additional filters [41], considering that emissions from steady state-based standard measurements significantly underestimate emissions under real operations [42]. Regular cleaning for ash removal (on a daily or weekly basis) and high noise levels in living spaces should be also taken into account. Room heaters can be integrated with water heat exchangers serving a hydronic circuit for in-floor radiant heating or DHW production.

Pellet stoves can be equipped with a water jacket connected to a hot water store through a heat exchanger placed in the middle of the storage (an electrical resistance can also be integrated), providing thermal energy – driven by the storage and the ambient temperature – firstly for DHW and then for space heating [43]. Solar collectors can be integrated in this set up by means of a heat exchanger immersed at the bottom of the buffer store. Typical efficiencies of these solutions vary between 80% and 90%. Alternatively, back boilers can be placed at the rear of the stove burning chamber (in place of the firebricks) connected, through a gravity convection system, to a storage tank from which water is delivered to the use-side circuits. All thermal energy stored through the heat exchanger should be dispersed to prevent overheating and water boiling (i.e., risk of explosions), and pressure/temperature relief valves should be installed in critical points. In addition, condensing heat exchangers can be optimised for the reduction of particulate emission from wood burning by condensation from

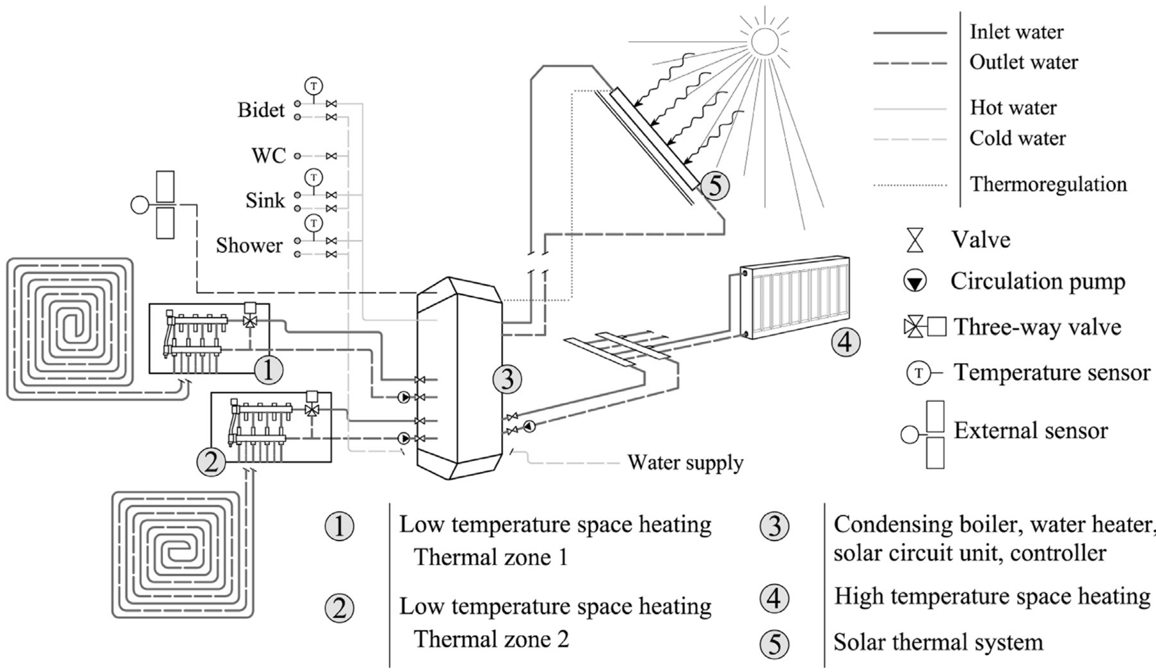


Fig. 2. Schematic of a condensing boiler working at three different thermal energy levels.

the flue gas flowing within the heat exchanger tubes (the water film formed on the exchanger surface allows the deposited particles to be removed [44]).

A further alternative to meet the ZEB low heating requirement is represented by slow heat-release stoves. A heat-conductive ceramic (or natural stone) storage core inside the stove absorbs over 60% of the energy produced in the combustion chamber which is gradually released as radiated heat at low temperature and slow rates per hour, with an 83% overall efficiency. The application of stoves to low energy houses is still in question because these stoves are generally oversized in comparison with the heating load of the house and the techniques to compute the contribution of the stove to the heating energy requirement of the all building are difficult. A study [45] has shown that the use of log stove is still critical in case of state-of-the market products and that log stoves with capacities smaller than 4 kW or with shorter combustion cycles should be developed. The low direct heat output prevents overheating. The thermal storage capacity is exploited to maintain ambient temperatures relatively constant for several hours after the combustion completion. Top wood burning reduces emissions whilst the low surface temperature of the stone cladding minimises dust circulation. Other alternatives to compact stone heat storages exist. Prefabricated double-walled heat storages with air gaps have a lower efficiency as compared to single-walled stoves without air gap [46]. A recent research carried out by the Danish Technological Institute and the stove manufacturer Morsø Jernstøberi has revealed the potential of using a phase change material – salt hydrate (melting temperature 60 °C) – in place of stone with a view to further extend heat quota released over time with lower mass and volume occupied. Tests have shown that temperatures above 30 °C have been maintained for more than 14 h after charging, thus eliminating night firing needs. Storage heating stoves can be also combined with heat exchangers to provide (or integrate) space heating. A hydronic module in contact with the stove storage core absorbs up to 50% of the energy produced, reducing the direct heat release through the ambient air, in a suitable way for low energy houses. Water flow is regulated through thermostat valves and a circulating pump.

Requirements and test methods for slow heat release appliances fired by solid fuel are provided by EN 15250 standard. However, only some theoretical studies exist on slow heat-release stoves [46].

2.3. Solar assisted heat pump

Another system that combines space heating and DHW production is represented by hybrid systems integrating solar thermal collectors and heat pumps for maximising the exploitation of renewable energy sources. Over the last years, a number of studies were carried out on solar assisted heat pump (SAHP) systems. A literature review on direct expansion (DX) SAHP is provided by [47,48] researches on DX-SAHP for space heating, SAHP for water heating, SAHP with storage for space heating and solar-assisted ground source heat pumps are reviewed by [49]. A mathematical model for DX-SAHP calculations consisting of energy and exergy balance equations is proposed by [48] and applied to a vapour compression DX-SAHP serving a Turkish office. In practice, different SAHP systems – equipped with unglazed evaporator collectors, evaporator collectors and air collectors, exploiting solar and ambient energy – were tested for various applications (air-conditioning, water heating, and drying) under the Singapore meteorological conditions in [50], resulting that, in comparison with a conventional collector, the evaporator–collector efficiencies were higher, ranging from 80% to 90% with an 8.0 coefficient of performance of the heat pump system. A variety of further investigations aimed at modelling, designing and testing solar assisted heat pumps systems is available in literature [13,51–53].

An example of an hybrid solar thermal-heat pump system is shown in Fig. 3: heat is generated by a heat pump; the primary loop of the solar thermal system serves a tank-in-tank storage volume (e.g., 750 l for space heating and 200 l for DHW); the DHW contained in the internal tank is sent to a heat exchanger for thermal integration operated by the heat pump.

Avoiding the thermal integration directly into the storage, allows the storage temperature to be lower and this increases the efficiency of the solar thermal collectors.

This system is usually tailored for detached houses; in multi-family residential buildings a centralised storage serving the solar thermal system and centralised or individual thermal integrations are provided. In this last case, heating energy metres are necessary.

2.4. Condensing boiler-heat pump

Whereas in the past several studies were conducted on heat pumps as stand-alone systems, new research efforts are currently directed towards the integration of heat pumps with other energy systems since hybrid systems represent a possible path to upgrade the heat pump technology extending it to wider applications [54]. Integrated approaches to the design of heat pumps are thus required in order to reduce costs and improve energy performances. Recently, hybrid systems combining a condensing boiler and a heat pump have been designed to take advantage of the benefits of each technology.

Considering a typical package with condensing boiler- air-to-water heat pump configuration, the heat pump runs when temperatures are mild; when the outside air temperature decreases, the heat pump's coefficient of performance (COP) decreases, while the heating load increases and the boiler is used since it is more convenient in terms of energy efficiency. A cut-off temperature below which the heat pump is switched over can be individuated based on the energy efficiency or on the energy cost; however it is also possible to activate the condensing boiler above the cut-off temperature when the heating load is not satisfied by the heat pump. Basically, the boiler is operative only when its efficiency is higher compared to the heat pump's equivalent heat efficiency, quantified in terms of source energy, which is dependent on the hot water temperature set point and the outside air temperature and relative humidity. This system has been proven to maximise the energy system total efficiency.

According to [55] the average seasonal energy efficiency ratio of such system amounts to 127%. Otherwise, heat pump and condensing boiler can be coupled separately without being combined into the same device. Fig. 4 shows an integrated system (1) which consists of a condensing boiler (3.3–33 kW), a 300 l stratified water heater and a solar thermal circuit. A 6–8 kW heat pump (2) is installed outdoor and is partly fed with the electricity generated by a photovoltaic (PV) system; DHW is produced by means of a plate heat exchanger.

In case the heat pump is reversible, for an optimal exploitation, a heat pump requires a balanced distribution of the heating and cooling loads throughout the year, which usually is not feasible in warm or cold climates, respectively demanding higher energy consumptions for space cooling and space heating (e.g., concerning ground source heat pumps, the amount of thermal energy injected/extracted into/from the soil) [56].

Not only electricity-driven heat pumps, but also other types of heat pumps can be coupled to condensing boilers. In comparison with an individual boiler thermal efficiency, a heat pump-boiler system fed by a low temperature heat source can reach up to 120% thermal efficiencies by coupling the heat exchangers in series and exploiting power recovery in the heat pump cycle expansion process [57].

An air-to-water gas engine heat pump coupled with two condensing boilers has been tested for three years by [58]: the heat pump was designed to meet the mean winter loads whilst the boilers integrated conjointly the primary hydraulic circuits (serving hot water at 40–45 °C) or separately (driven by thermostats) the primary and the secondary circuit (with 70 °C hot water from the heat recovery). The gas engine heat pump and the condensing boilers have also been compared by running separately during two series of three testing days: the condensing boiler performance appeared quite lower, attesting 20% higher consumptions. Vice versa, significant energy savings have been attested by the HVAC plant operating as a whole, rationally exploiting the peculiarities of these two production systems.

In addition, the condensing boiler has also been integrated with absorption heat pumps (reviewed below): in this combination, the boiler is also used to increase up to 80 °C the thermal level of the hot water produced by the absorption heat pump.

2.5. Zeolite based integrated system

The continuous research for an alternative energy source contrasting fossil fuels worldwide demand has been a driver to discover new materials or innovative uses of already known technologies. Zeolite is an aluminosilicate mineral whose physical properties make its use complementary to heat pump cycles. Thanks to its hygroscopic microporous molecular structure, the zeolite is able to store heating and cooling energies by adsorbing water vapour and releasing thermal energy through reversible water adsorption/desorption cycles. In particular, zeolite's high thermal energy storing capacity, along with its ability to undergo several reversible direct hydration and dehydration cycles, result ideal for thermal energy storage systems [59]. In thermal driven adsorption heat pumps, zeolite operates as adsorbent. The adsorbate should have well-defined features (e.g., compatible, non-toxic, non-flammable, stable): water is often used due to a higher latent heat per volume capacity in comparison with traditional refrigerants [60]. Several researches for different applications have been carried out on zeolite-water working pairs [61–63].

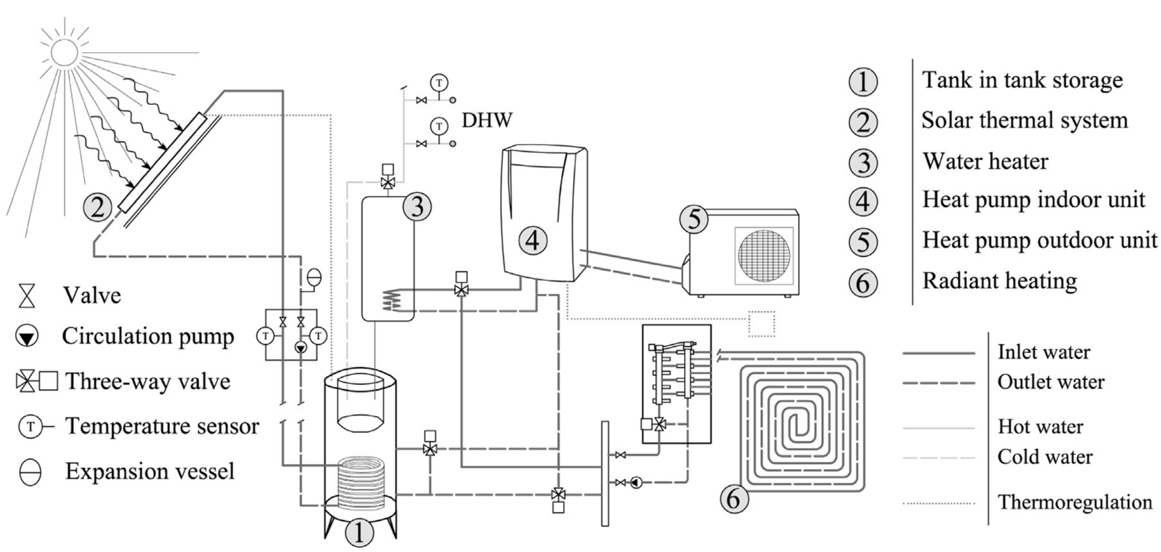


Fig. 3. Schematic of a solar thermal plant for space heating and DHW production coupled to an heat pump.

Adsorption heat pumps have the potential for being economically competitive [64] with vapour compression heat pumps due to many advantages such as longer life span, quiet running, lack of moving parts and hazardous materials [65]. On the contrary, lower COP, leakage, high vacuum and, particularly, heat and mass transfer problems represent the main drawbacks [65,66].

A typical zeolite/water gas heat pump is coupled with the well-known gas condensing boiler with solar supported heating. Designed with capacities from 10 to 15 kW and efficiencies up to 128%, this system provides DHW and low-temperature space heating for single-family detached houses. A schematic of this system is reported in Fig. 5. The heat pump module contains a heat exchanger, placed at the top, which is filled with zeolite granulates and works as an adsorber/desorber, whilst a further heat exchanger at the bottom of the module acts as condenser/evaporator; in addition, water operating as refrigerant is adsorbed by the zeolite or collected at the lower part of the module.

During the desorption phase, the boiler burner increases up to 120 °C the heating fluid running within the adsorber/desorber and as a consequence the water previously embedded within the zeolite crystals reaches in the form of steam the lower section of the module, where it condenses releasing thermal energy until the zeolite gets dry. At this stage, with the gas burner switched off, the module is gradually cooled and the adsorption phase begins: exploiting the heat from the solar circuit, the water stored at the bottom of the module evaporates and raises to the adsorption section where it is again stored within the zeolite, closing the cycle.

The zeolite storing capacity remains unchanged ensuring effective operation even after thousands of adsorption/desorption cycles. Further advancements on zeolite based integrated systems – basically still a niche technology – are expected also in virtue of the non-toxic and non-flammable nature of the material.

2.6. Multi-source storage

Bridging the gap between energy consumption and energy generation is necessary to rationally exploit the various energy sources (both renewable and conventional) [67], and energy efficient technologies for thermal energy storage have been increasingly studying since indispensable to balance the mismatch between energy generated and energy consumed by optimising energy management strategies. Stritih et al. [68] gave an overview of state-of-the-art advancements in solar thermal energy storages, with particular reference to the Turkish and Slovenian context, distinguishing between short diurnal (day/night) and long seasonal (summer/winter) storages – the former using mostly phase change materials (PCM) and thermo-chemical applications, the latter usually provided with underground thermal energy storages – and an hybrid system combining both. The exploitation of latent heat by means of the aforementioned PCMs appears an effective way of storing thermal energy, and a significant literature on this matter is available, such as [69–71], however according to IEA Task 32 [72] further research is necessary for PCMs screening, heat transfer optimisation, stores design and simulation models.

Therefore storing energy in the form of sensible heat currently appears the most viable solution for seasonal storage of thermal energy since cheaper, reliable and well-established [73]. The main drawback of this solution is the high thermal level required to the storage medium in order to dispose of an adequate energy density, i.e., without a marked stratification the heat transfer to a storage almost charged becomes problematic as well as it reversely is the exploitation of low valued thermal energy when the storage is going to discharge [73]. Thermal stratification should therefore be accentuated as much as possible, also in view of upgrading the solar thermal system efficiency (by 5–15% compared to a water mixed storage [74]) by exploiting the outlet fluid low thermal level which allows to minimise the heat exchange between solar collectors and the environment [75].

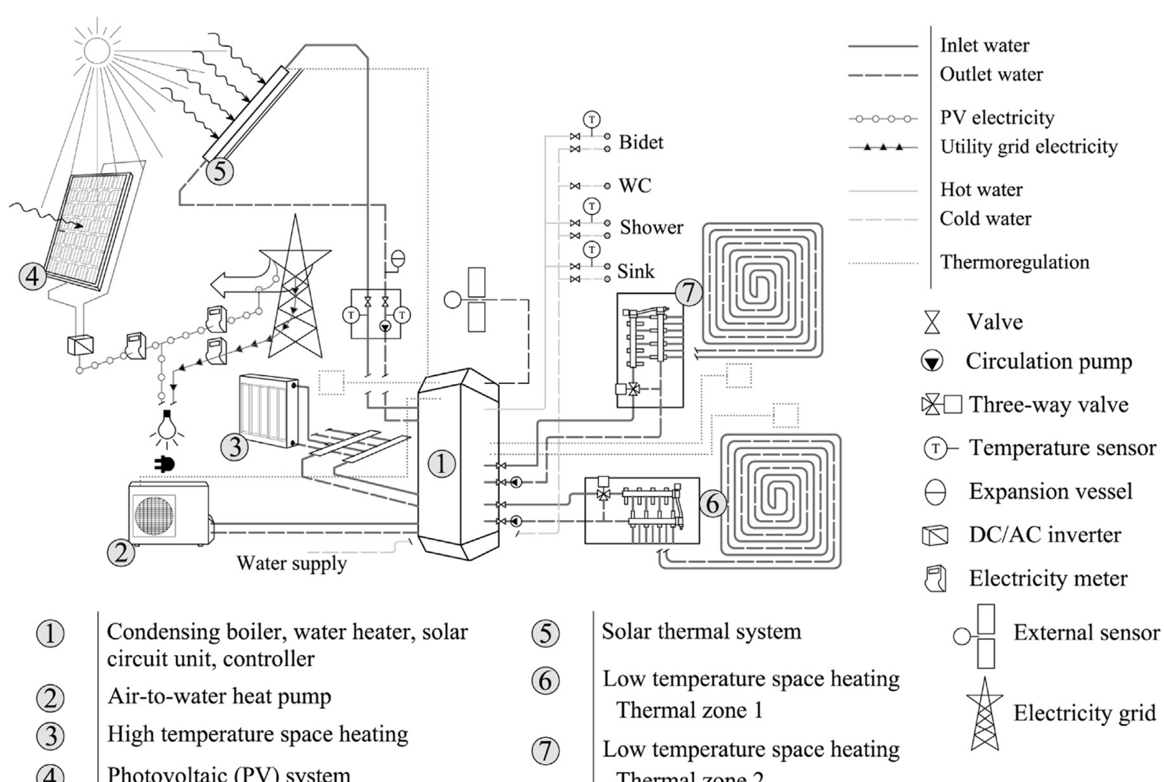


Fig. 4. Schematic of an air-to-water heat pump, condensing boiler, solar thermal and solar photovoltaic system.

Research efforts have been aimed at optimising stratification, for instance by means of stratifiers propaedeutic to decrease mixing phenomena within the water volume [76], exploiting segmenting storage systems [77] or enhancing the stores configuration [78].

To this regard and with a view to optimising the exploitation of different energy sources (in particular the renewable ones) providing hot water at different thermal levels, multi-source multi-use water heat storages were recently designed. Those multi-source multi-use storages consist of:

– different hydronic *source side* circuits fed by solar thermal, biomass boilers, gas boilers and so on;
– different hydronic *use side* circuits, such as high temperature space heating (e.g. radiators) and low temperature radiant space heating, DHW; and
– a controller which optimises the exploitation of the source side of the storage according to the use side. The source side and the use side can be connected hydraulically or by means of a heat exchanger.

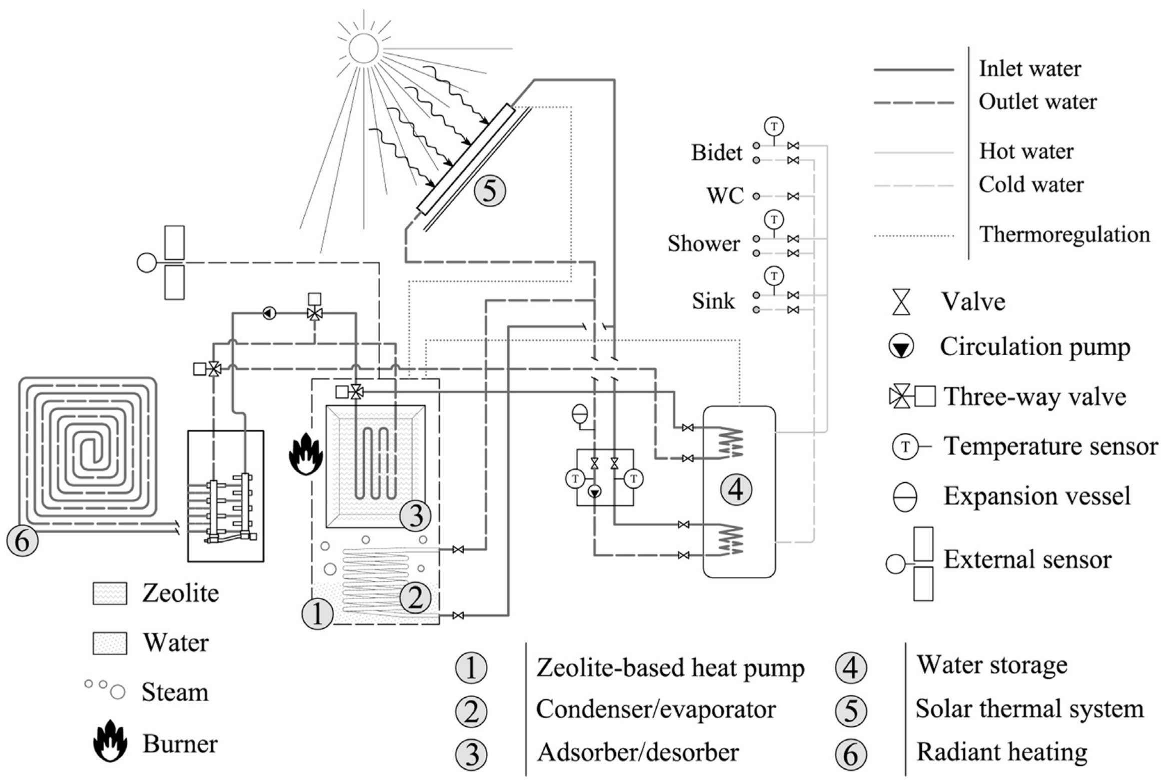


Fig. 5. Schematic of a zeolite-based integrated system for space heating and DHW production.

–

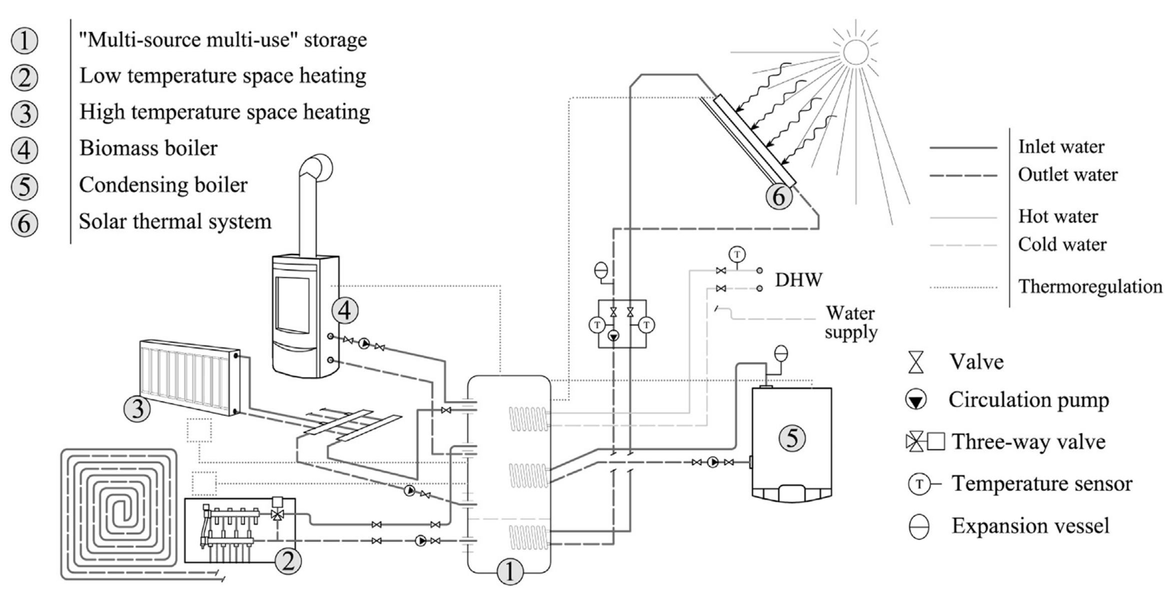


Fig. 6. Schematic of a thermal plant provided with multi-source multi-use storage.

Multi-source multi-use storages rely on the water volume thermal stratification to improve the heat transfer performance: in the inside, heat exchangers are properly placed in relation to the expected fluid operating temperature, which rises upwards. In order to have the best possible pronounced temperature stratification behaviour, interior diaphragms are used and geometry of the use and source side heat exchangers is designed to minimise convective heat and mass transfer within the tank. A schematic of a multi-source multi-use energy storage is reported in Fig. 6: lower coils receive heat from solar thermal (or, alternatively, heat pumps or heat recovery from chiller condensers); intermediate coils receive heat from the condensing boiler; upper coils are used to produce DHW. The heat storage is hydraulically connected to high and low temperature space heating uses (e.g., radiators and radiant panels) and to a biomass boiler.

The temperature stratification can be further enhanced by exploiting direct storage of the heat into the solar thermal storage with unpressurised and direct drain-back systems. A 300 l stratified solar storage is integrated with a gas condensing boiler or heat pump in small compact units (e.g., 0.36 m^2) for water heating and space heating integration. The storage is equipped with up to four steel pipes heat exchangers and is fed only once during the commissioning with unpressurised and additive-free tap water. At the bottom of the store a heat exchanger is fed by cold water, whose temperature rises upwards along the storage accentuating the system stratification behaviour and ensuring low thermal levels serving the solar thermal circuit. Thermal energy is directly stored into the tank, and since the DHW flows in a separate pipe system instead of being as usual stored in the storage volume, it is possible to prevent deposits of sediments and also legionella bacteria growth due to the uniformity of the water flow within the store which is homogeneously heated. The water is directly provided to the solar collectors without heat exchanger and once heated it is redirected to the store and stratified. The absence under specific boundary conditions of a working fluid running within the collectors allows to avoid the use of antifreeze agents; in addition, due to the unpressurised operation, the adoption of ancillary equipment such as pressure gauge, expansion tank and pressure relief valve is not required. However, this solution is feasible only with specific tilt angles for the connexion pipes and heights which can be covered by the pump.

3. Integrated systems for space heating, cooling and DHW

3.1. Reversible heat pump

The most recurring solution integrating space heating, DHW and space cooling is based on the reversible heat pump technology. Basically, heat pumps allow to transfer thermal energy from a low temperature medium to a high temperature medium. A heat source is used as a medium to extract thermal energy through an evaporator and a heat sink is used as a medium to reject thermal energy through a condenser [79]. Usually, a working fluid is compressed into liquid and expanded into vapour absorbing and releasing thermal energy. In order to invert spontaneous heat flow from higher to lower temperatures, an amount of external energy is necessary, which is proportional to the outdoor-indoor temperature gradient.

Recent upgrades led heat pumps to produce, along with hot and chilled water for space heating and cooling, also hot water for domestic use at appropriate thermal levels. DHW energy demand is time concentrated but constant throughout the year, accordingly it has to be provided also in cooling mode (for instance by condensing heat recovery).

For low energy demand users, reversible heat pumps with heat recovery are currently very commonly adopted, operating on "single-stage" (space heating or space cooling or DHW) and "two-stage" (space heating and DHW, space cooling and DHW with heat recovery).

For intermediate and high energy demand users, hot/chilled water can be provided by means of reversible heat pump while a separate heat pump (or another production system) is dedicated to the DHW production. For a cooling/heating capacity from 5 kW to 20 kW, the heat pump is an air cooled or water cooled packaged system assembling a thermal/chiller section, a hydraulic section with storage and pumps and a controller section. It is then sufficient to properly connect the different hydronic circuits (space heating/cooling, DHW, solar thermal, condensing fluid or refrigerant depending on whether the heat pump source is the water or the outdoor air). However, COP of heat pumps is highly variable and dependent on heterogeneous factors such as system components, source temperature, medium used [48]. In particular, the following boundary conditions considered to assess the heat pump/refrigerator nominal capacity and COP/EER should be carefully fixed:

- hot/chiller water supply temperature and delta temperature difference (ΔT);
- evaporator/condenser source side temperature.

The heat pump/refrigerator performance indicator provided by manufactures is assessed at a pre-defined set of operating conditions (reported for example in the Eurovent Certification): the congruity between expected and real operating conditions should be therefore meticulously evaluated. An air-source heat pump whose COP has been assessed assuming a 35 °C hot water supply temperature for space heating (on the lower limit for low-temperature space heating) should be congruent with the design of the heating terminals. In order to exemplify, COP and heating capacity variations for a liquid refrigerator operated in heat pump in relation to different evaporator temperatures (13 °C and 18 °C) are reported in Fig. 7, whereas Table 1 shows how a water-to-water heat pump and an air-to-water heat pump seasonal COPs (SCOP) and seasonal EERs (ESEER) vary in relation to different operating conditions.

According to Fig. 7, when the condensation temperature rises from 35 to 55 °C, COP is almost halved and the heating capacity shows a downward trend loosing approximately 5 kW.

Furthermore, it is important to evaluate the operating temperature intervals since the hot water supply temperature can decrease when the outside air temperature drops. Accordingly, advanced versions of these energy systems are also provided with

- an additional thermal resistance that guarantees DHW production when the outside air temperature is lower in case of air-source heat pumps;
- an exchanger which permits free-cooling without operating a refrigeration cycle and exploits direct heat exchange with lower cooling water temperature in case of water-source heat pumps.

Part load performances – required to carry out the seasonal performance assessment – should be also considered and can be synthetically represented by means of diagrams like those reported in Figs. 8 and 9, where COP and EER trends are shown for 30%, 40%, 50%, 60%, 75% and 100% load factors according respectively to a 35 °C and 18 °C outlet water temperature.

Small capacity heat pumps are usually provided with scroll compressors and use the R-410A refrigerant; their performance is then improved at lower loads.

In addition, heat pump systems with total heat recovery are designed to combine hot/chiller water and DHW production. Domestic water heating is provided by means of a steel plate heat exchanger placed after the compressor and operating in total or

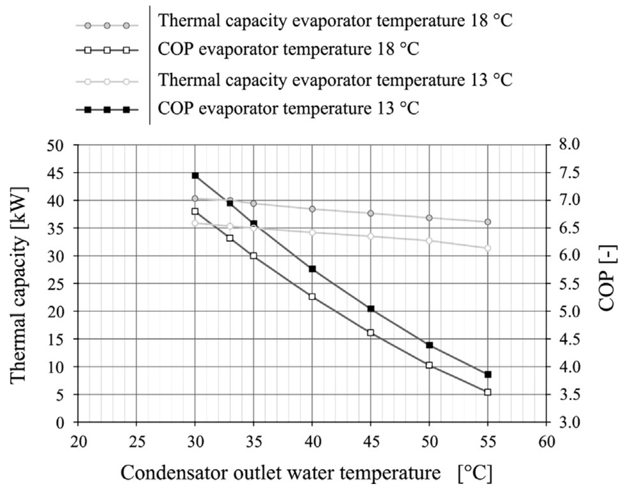


Fig. 7. Different COPs varying the condensing fluid temperature for a 29 kW heat pump.

Table 1
Water-to-water and air-to-water heat pump seasonal COP and seasonal EER according to different hot/chiller water supply temperatures.

T_{out}	Water-to-water heat pump		Air-to-water heat pump	
	SCOP	ESEER	SCOP	ESEER
35 °C	5.70		3.76	
45 °C	4.72		3.35	
18 °C		5.48		5.23
7 °C		4.59		4.02

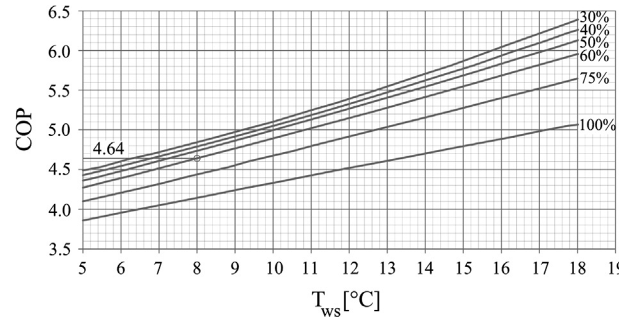


Fig. 8. COP variation in relation to the water source temperature (T_{ws}) according to varying loads for a small capacity water-to-water heat pump/refrigerator for residential applications; the outlet water temperature is set to 35 °C.

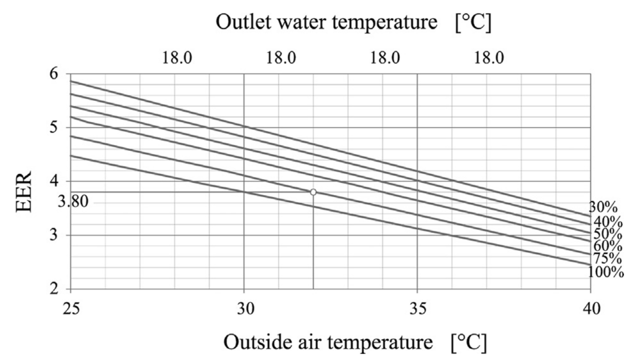


Fig. 9. EER variation in relation to the outside air temperature according to varying loads for a small capacity air-to-water heat pump/refrigerator for residential applications; the outlet water temperature is set to 18 °C.

partial recovery mode. Data retrieval for energy consumption calculations is again time-consuming since specifications concerning the system performance are required in relation to different operating conditions and are not commonly found on manufacturers specifications.

3.2. VRV/VRF system

Hot/chilled water for space heating & cooling and DHW can be also produced with hybrid variable refrigerant volume (VRV) or variable refrigerant flow (VRF) systems. Basically, a VRF system exploits a variable speed compressor and the indoor units electronic expansion valves to vary the refrigerant flow rate in order to cover the heating and cooling loads and reach the set-point temperature. A detailed overview on operations, applications and costs and a review of the experimental and numerical researches carried out on multi-split VRF systems can be found in [80]. A control method for a multi-split VRF system, developed in [81], demonstrates that in a room with high cooling load the indoor unit refrigerant flow rate is higher compared to the one of the indoor unit, and that reaching the set point temperature the compressor's frequency diminishes; the refrigerant flow rate of the indoor units can be individually controlled being responsive to the cooling loads. A further control strategy with a fuzzy control algorithm aimed at reaching the desired level of control of multi-evaporator air conditioners is proposed and tested in [82]. Recommended superheats in indoor units should be kept around 4 °C by regulating the expansion valves whilst the compressor speed is adjusted according to the units optimal cooling capacity [83]. VRV can be also provided with a digital scroll compressor instead of recurring to the inverter technology, with high performances and cost effectiveness (20% cost savings compared to an analogous solution with inverter aided compressor) [84]. There is still a shortage of energy simulation software available for the energy performance assessment of VRF systems, however the Energy Plus environment can be used for investigating VRF modules and comparing their effectiveness in relation to other energy systems [85].

Used at first in DX units, currently VRV systems can be equipped with refrigerant-water heat exchangers in order to be used also in hydronic systems [86]. In Fig. 10 the schematic of a gas-water hybrid energy system is shown. DX terminals on the refrigerant loop are associated with heating/cooling water units of the hydronic circuit, equipped with pumps and an optional storage. R-410A refrigerant is used and it is possible to produce hot water at a thermal level around 45 °C. In this case, the system consists of an air or water condensing external unit, a refrigerant loop, air internal units and water condensing/evaporating units producing hot/chilled water. COPs depend on the boundary conditions concerning design heating and cooling water temperatures, fluid temperatures at the cold side (air/water) and hot side. Through external units with heat recovery in VRV and VRF systems, in addition to simultaneously activate different DX internal units in heating or cooling setting, it is possible to produce at the same time hot/chilled water via water/air terminals.

As shown in Fig. 11, hot water at higher thermal levels (up to 70 °C) can be provided by partialising the thermal lift, i.e. coupling another heat pump using the R-134a refrigerant to the primary R-410A refrigerant circuit. The hot water supply system allows to recover thermal energy extracted from thermal zones which undergo space cooling to integrate hot water production covering only, if necessary, the remaining quota of the heating load.

This solution avoids the COP of the external unit to be excessively reduced while guarantees hot water at two different thermal levels. Installing a water condensing external unit, it is

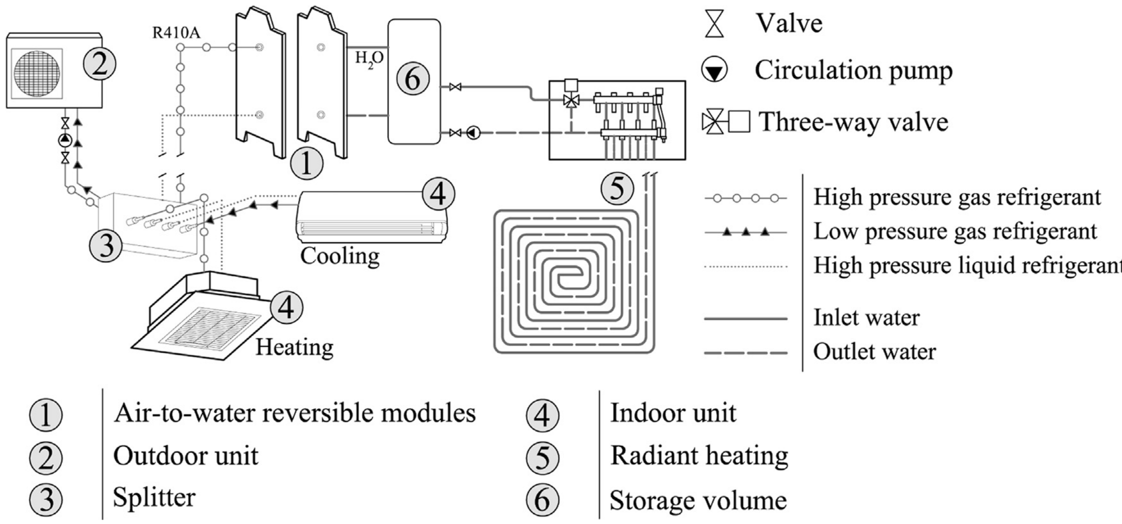


Fig. 10. Schematic of the refrigerant loop serving a VRV system equipped with air-to-water unit for intermediate/low temperature hot water production and chilled water production.

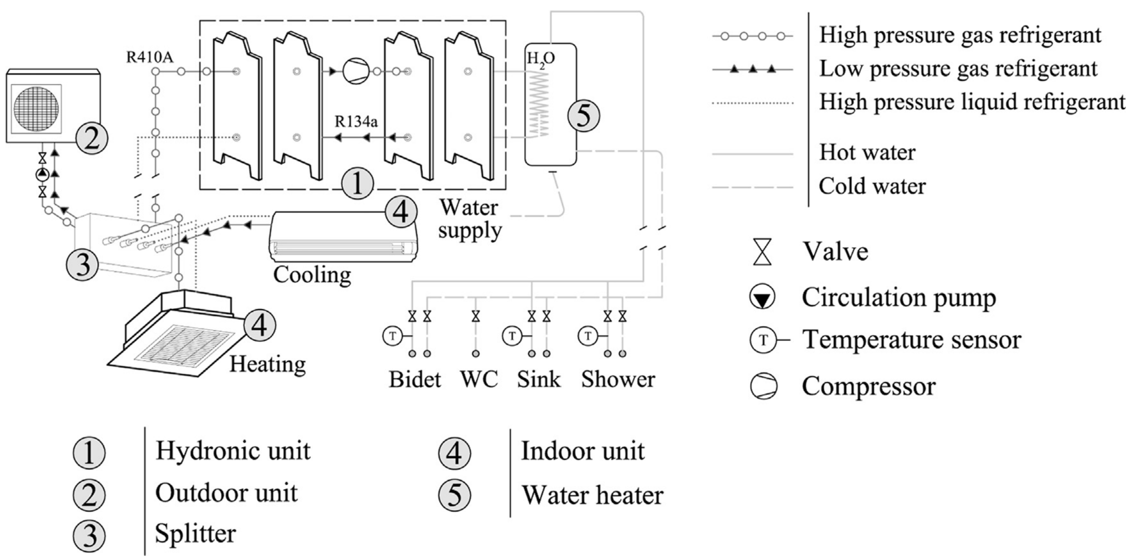


Fig. 11. Schematic of the refrigerant loop serving a VRV system equipped with a two-stage hydronic unit for high temperature hot water production.

possible to produce hot water at 70 °C reaching a 3.5 global COP (including both heat pumps). It is worth noting that also these energy systems can be connected to the solar thermal circuit, as demonstrated by the plant scheme reported in Fig. 12, where the outside air thermal energy is exploited by the outdoor unit and then delivered through a refrigerant circuit to the water unit where it is transferred to a hydraulic circuit serving the space heating and DHW production.

3.3. Gas heat pump

Along with vapour-compression heat pumps with electricity-driven compressor, there are also vapour-compression gas engine heat pumps (GEHP) whose compressor is driven by an endothermic engine and gas-fired absorption heat pumps (GAHP), both tailored for intermediate sizes. GEHP technology, up-to-date basically uncommon, uses a gas-powered endothermic engine that operates the refrigeration compressor of a conventional reverse vapour-compression cycle: in heat pump setting, during winter, heat recovery operated by the engine (from the cooling of the cylinder and from the exhaust recovery) is exploited to evaporate the refrigerant (Fig. 13, on the top); during summer, with the reverse cycle activated, the heat recovery from the engine is used for domestic water heating (Fig. 13, on the bottom). GEHP heating capacities range from 25 kW to 80 kW.

A comprehensive overview on historical development, literature and operation of gas engine-driven heat pumps, in addition to energy and exergy balance equations defined for an illustrative example, is provided by [87]. Initially investigated at the end of 1970s [88,89], the first gas engine-driven heat pump was commercialised in 1985. The rationale behind its adoption lies in the possibility of replacing electricity with natural gas (apart from parasitic power consumptions), avoiding the twofold conversion fuel-electricity at the power plant and electricity-mechanical energy by the heat pump, with an efficiency ratio amounting to roughly 140% in cooling mode (with free DHW production) and 150% in heating mode. The COP of gas engine-driven heat pumps is not considered suitable for comparative purposes since not properly influenced by the heat recovery effect. For that reason the primary energy ratio (PER) is preferred [87]. The gas engine heat

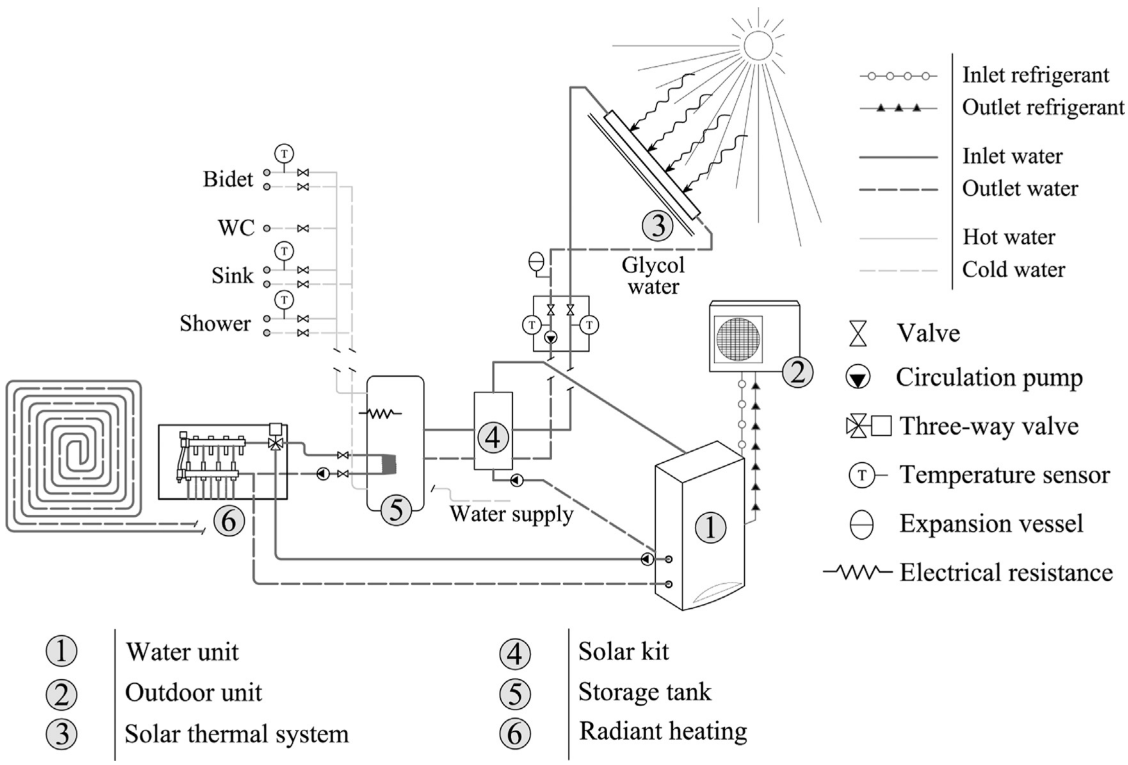


Fig. 12. Schematic of a VRV system equipped with water units and solar thermal integration for space heating & cooling and DHW production.

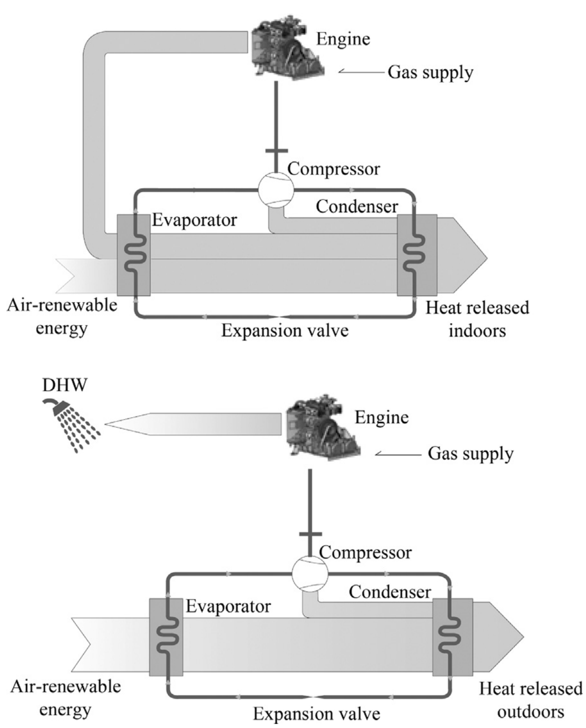


Fig. 13. GHP working diagrams.

pump PER is proven to be the highest amongst different heating and air-conditioning systems evaluated under various conditions [90,91]. However, further advancements in control systems and equipment appear necessary in the development of gas engine heat pumps [87]. Hybrid systems that combine gas engine heat pumps with other technologies and systems are also studied to reach higher efficiencies compared to conventional gas engine-driven heat pumps [92,93].

3.4. Gas absorption heat pump

An absorption cycle is basically used to bring low-valued energy (e.g., geothermal energy, solar energy, and heat recovery), to a useful temperature level; absorption-based systems are interesting in virtue of the high energy savings potentials and, in contrast with most vapour compression systems, due to the avoidance of the use of chlorofluorocarbon refrigerants [94]. Fig. 14 shows two GAHP units running for space heating and DHW production with the integration of a boiler.

The GAHP operates with an ammonia and water solution which is heated by a gas fired burner and then transferred to the condenser where condensing releases thermal energy which is used for DHW production and space heating. Through an expansion valve, the high pressure ammonia liquid is converted into low pressure ammonia liquid which evaporates in the evaporator exploiting the outside air thermal energy content. Within the absorber, the ammonia gas is dissolved into the ammonia water solution and a pump drives a new process so that the cycle can repeat.

A GAHP fired with methane can provide a gas utilisation efficiency (GUE) for space heating from 150% to 170%, depending on the expected hot water supply temperature and selected evaporator heat source (air, water, ground). The lower efficiencies are characteristics of air evaporating heat pumps and DHW production at a higher thermal level (50 °C). The hot water supply temperature can be increased coupling a GAHP with a gas-fired condensing boiler: accordingly, temperatures can increase up to 80 °C, suitable for DHW storages or peak loads coverage on a limited time period. GAHPs achieve approximately a 70–80% energy efficiency ratio operating in cooling mode; similarly to GHP systems, DHW is generated by means of the condensing heat recovery. In addition, in virtue of GAHP lower

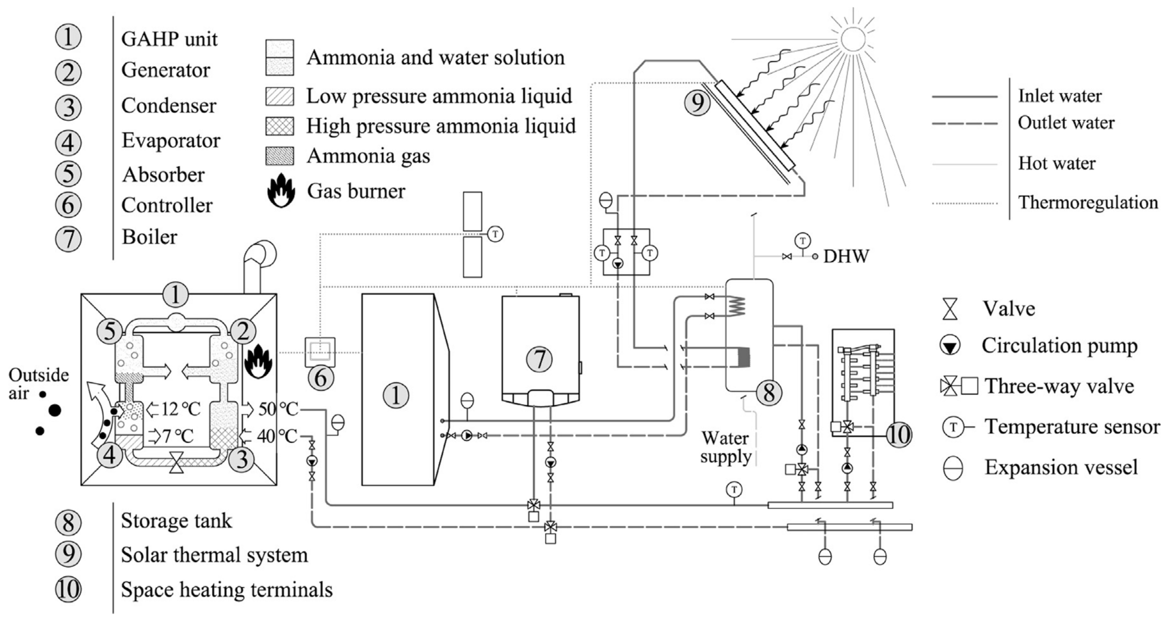


Fig. 14. Schematic of methane-fired absorption units providing space heating, refrigeration with heat recovery and DHW.

cooling energy efficiency ratio, potentially recovered condensing heat is higher in comparison with vapour-compression GHP systems in cooling mode.

According to annual primary energy consumptions and greenhouse gas emissions, an air-to-water GAHP is proven by [95] to be one of the most effective solution for a hypothetical 100 m^2 house located in a variety of European climates. Nevertheless, small sizes unavailability due to a still limited diffusion for smaller applications often leads to oversize the GAHP capacity resulting in higher energy consumptions which annul the effectiveness of this solution. Accordingly, on the residential market this energy system cannot yet be considered competitive for single-family houses. Further considerations on the economic viability of GAHPs can be found on [96], where the energy savings obtained for different uses by absorption heat pumps with high annual utilisation allow a limited pay-back period of only a few years. The overall energy performance of a GAHP could be further enhanced through the exploitation of multi-energy sources such as geothermal, solar energy and heat recovery, as demonstrated by field tests carried out by [97].

However, even though promising from a theoretical point of view, DHW production based on heat recovery should be in all cases carefully evaluated in relation to the operation at part load, the temporal mismatch between cooling load and DHW load and, more generally, the effective operation in mid-seasons. In light of these considerations, a complete thermal recovery during the summer cannot be considered feasible.

3.5. DHW production peculiarities

With regard to the DHW production, heat pump water heaters, as shown in Fig. 15, operate on an electrically driven vapour-compression cycle and instead of using gas burners or heating coils, they exploit the outdoor air thermal level to heat the water stored within a tank [98]. Being equal the electric input, this solution is more convenient in terms of heat generated compared to standard water heaters [99], with expected energy savings ranging from 55% to 70% – lowered in the range 38–60% by a series of field tests [98,100]. However, the adoption of a heat pump water heater should be critically evaluated. The main peculiarities concerning water domestic heating and their repercussions on DHW production by means of heat pumps are the followings:

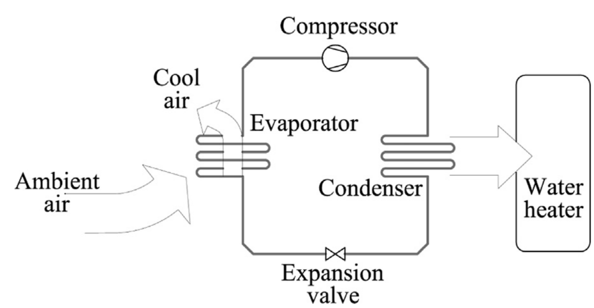


Fig. 15. Simplified schematic of the operation of a heat pump DHW water heater.

- DHW has relatively high thermal levels (45–60 °C), in general exceeding the low-temperature space heating thermal levels (35–45 °C) suitable for heating systems coupled to heat pumps;
- the DHW energy demand is concentrated in time but constant throughout the year;
- for ZEBs, the DHW heating load is more than double in comparison with the space heating load (e.g., 18 kW load for a DHW flow rate of 10 l/min with a delta temperature between 15° and 40 °C); and
- for ZEBs, the energy demand for DHW production may frequently be higher than energy demand for space heating.

Consequently, instantaneous DHW production is not feasible when heat pumps are used for space heating: a storage volume is firstly necessary to level the DHW load allowing a continuous operation and appropriate temperatures for both use side (hydronic circuit) and source side (heat pump condenser). Furthermore, typically at around 0 °C, a back-up electric resistance is needed due to the limited ambient heat availability and the condenser is submitted to defrost cycles, resulting in lower coefficients of performance [98]. In addition, peculiarities related to integration with one or more renewable energy source – a key aspect which is

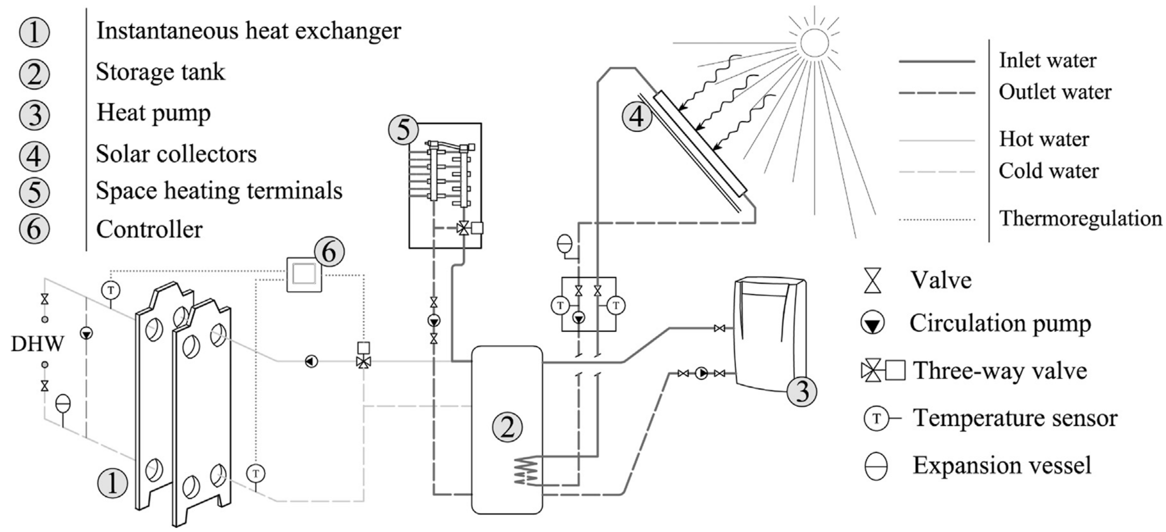


Fig. 16. Schematic of water storage and DHW instantaneous heat exchanger.

mandatory in many European countries – should be also taken into account.

There are basically three different technologies that are applied in vapour compression heat pumps in order to produce high temperature DHW:

- the use of an economiser on the refrigeration cycle;
- a double-stage vapour compression refrigeration cycle that works with two fluids; and
- the use of a desuperheater on the refrigeration cycle.

In the first case, the economiser is placed between the condenser and the expansion valve. Part of the liquid that exits the condenser is spilled and undergoes a first flash evaporation through an expansion valve, refrigerated up to the temperature of phase change corresponding to the output pressure from the first stage of compression. Subsequently, the refrigerant enters the economiser where it evaporates and removes heat from the remaining part of the condenser liquid outlet, and goes through the second stage of the compressor. This approach, widely adopted for large capacity scroll and centrifugal chillers, has been lately adopted also for heat pumps that are used to produce DHW. The economiser increases the COP and it is useful for heat pumps whose condensation pressure is high due to the requirement on the water production side, as in heat pumps for DHW. In this technology, the maximum water side temperature that can be reached is 65 °C for R410a refrigerant and 67 °C for R134a refrigerant.

For a DHW production at around 70 °C it is necessary to adopt the second technology, that is a double-stage compression cycle. With regard to the refrigerants, R410a, or sometimes R404a, is used for the first cycle (production of space heating hot water) and R134a is used for the second high temperature cycle (production of domestic hot water).

In the third case, the desuperheater is placed between the compressor and the condenser: the superheated vapour is first cooled into the desuperheater to produce high temperature hot water, then condenses into the condenser to produce medium temperature hot water. In this technology, the DHW load can be at maximum 25% of the total heating load and can only operate simultaneously with the space heating load.

This technology is therefore preferable when the high temperature DHW heating load is contemporary with the medium temperature heating load and it represents a small portion of this last one.

For what concerns the plant schemes, there are at least three possible configurations [101]:

- DHW storage with internal coil (water heater);
- DHW storage with external plate heat exchanger; and
- storage of "technical" water and instantaneous heat exchanger for DHW production.

Through the first solution, the storage volume can be sized for the DHW demand, however an appropriate storage coil has to be designed in relation to the heat pump (with larger heat exchange surfaces) taking adequate precautions to avoid legionella proliferation (e.g., thermal shock with programmable electric resistance).

As the first, the second solution consists of a storage volume designed on the DHW demand, but the external heat exchanger is characterised by a higher efficiency: it does not activate convective movements within the storage which is more efficiently discharged, exploiting the piston effect provided by the feed of cold water. Reversely, two pumps (primary loop and storage loop) operate with higher electricity consumptions and, again, measures to prevent legionella should be implemented.

The third solution (Fig. 16) permits to instantaneously produce DHW using a flat plate heat exchanger placed outside the storage which is filled with "technical water" and there is no problem of the legionella proliferation. Fig. 16 shows a DHW production unit equipped with a modulating pump with electronic regulator providing from 25 to 200 l/min DHW through a stainless steel plate exchanger, with electronic reset of DHW temperature, recirculation temperature and operation schedules. However, due to a larger volume, in this solution the storage sizing results more problematic. Indeed, in order to meet a use-side of 45 °C water target temperature, the exchanger is fed by technical water provided at an adequately higher temperature, such as 47 °C, and as a result the storage would be theoretically already discharged when uniformly at 47 °C. Two pumps are operative also in this configuration: with high DHW loads, this is no convenient.

In Fig. 17 a diagram shows the performance of an instantaneous DHW water heater (heat exchanger) coupled to a heat pump, reporting the water flow rate as a function of the temperature of the technical water delivered to the inlet of the exchanger (in abscissa) and utility side (T_{in}) and use side (T_{out}) water temperatures. It is possible to observe that, in correspondence of the lower boundaries of the operating profile, the temperature of the water flowing within the technical water primary circuit should be at

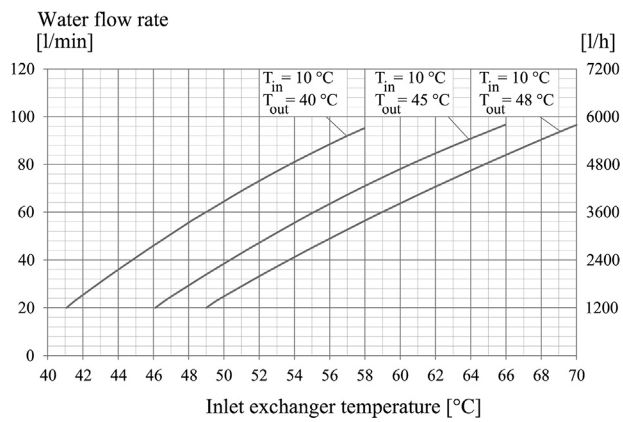


Fig. 17. Performance of an instantaneous heat exchanger for DHW.

least 1–2 °C higher than the target DHW temperature and that, with the same ΔT between inlet and outlet DHW temperatures, a higher inlet water temperature of the primary circuit is necessary to increment DHW flow rate.

A wide literature is available on heat pump water heaters. An air source heat pump water heater, composed by a heat pump, a water tank and connecting pipes, is described in [102]: thermal energy is absorbed through the evaporator and transferred to the storage tank; water is heated to the 55 °C set point temperature using a rotary compressor. In view of being adopted in zero net energy homes, the performance of a heat pump water heater has been compared with other DHW productions systems which exploit renewable energy – a regular electric hot water tank; the desuperheater of a ground-source heat pump with electric backup; thermal solar collectors with electric backup: the latter resulted the most effective system under the Montréal and Los Angeles climates [103]. Further advancements in heat pump water heaters are expected, researches have been carried out on innovative configurations such as instantaneous water heaters which integrate a thermoelectric heat pump with separating thermosiphon [100] and heat pump water heaters equipped with CO_2 working fluid with a 4.3 COP (heating tap water from 9 °C to 60 °C at an evaporation temperature of 0 °C) able to smoothly produce up to 90 °C hot water [104].

4. Integrated systems for space heating, electricity and DHW

Cogeneration (CHP) is the simultaneous production of thermal energy and electricity exploiting a single energy source such as gas, biomass or solar. Combining two different forms of energy in one process, it is possible to overcome the efficiency limits characteristics of separate production systems. According to [105], conversion efficiencies rise from 30% to 35% of conventional fossil fired electricity generation systems to over 80% of cogeneration systems. Therefore, despite a higher fuel consumption is necessary to combine heat and power production, the same amount of energy potentially obtained by separate systems can be produced with less fuel, and the effectiveness of this system is maximised relying on renewable energy sources [106]. Accordingly, particularly in the United States, Japan and Europe, an increasing attention is being directed towards the adoption of small size cogeneration systems also within the residential sector [107]. A thorough overview on microcogenerators fired with natural gas can be found in [108]. Currently, internal combustion engine based CHP systems is the most viable system for residential applications [109], however emerging micro-turbines, Stirling engines and Dish/Stirling solar technologies have the potential for being successful in the near future.

4.1. Internal combustion engine based CHP

Cogeneration systems driven by an internal combustion engine can rely on a consolidated technology and a variety of energy sources [110]. A typical configuration comprises an engine which activates a generator – whilst Diesel engines generally run on larger plants, spark ignition (Otto) engines fired with natural gas are usually tailored for smaller sizes [105] – the controls and an exhaust and heat recovery system providing useful heat from the exhaust and cooling systems [111–113]. Condensing heat exchangers can be used for latent heat recovery. Due to their limited size, systems based on traditional internal combustion engines powered by gas are necessarily characterised by relatively low electrical efficiencies, from 20% to 30%, and thermal efficiencies between 60% and 70%. The economic feasibility of these systems depends on correct sizing, running hours throughout the year and considered feed-in tariff for feeding energy into the grid; an up-to-date review of different feasibility evaluations can be found on [114].

Fig. 18 shows an integrated system for space heating, DHW and electricity production serving a multi-family residential building: the cogenerator is equipped with an inertial thermal energy water storage, integrated by modular wall-mounted boilers and use-side heat metering. The cogenerator, which can be powered by natural gas, propane, gasoil or biodiesel, can be equipped with an additional heat exchanger for condensing exhaust gases. This system allows to fully exploit the potentialities of the condensation process lowering to 35 °C the hot water return temperature, reaching global efficiencies (that is efficiency which includes both electric and thermal ratios), near to the unit.

4.2. Stirling engine based CHP

New microcogenerators launched for the residential market by several manufacturers are based on external combustion engines operating according to the Stirling cycle, which ideally resembles the Carnot cycle [115]. Through a succession of adiabatic and isothermal processes, thermal energy is converted to mechanical energy used to power a generator and produce electricity. Waste heat from the engine is exhausted to the atmosphere through a cooling system driven by a parasitic power consumption. The adoption of Stirling engines has recently grown with the launch of the free piston technology [116,117]. Different Stirling engine based units have been introduced on the small scale (e.g., 1 kW of power), with electrical efficiencies in the order of 12–16% [118]; Stirling engines below 20 kW are expected to operate from 5000 to 8000 running hours without significant mechanical maintenance [105]. These devices, installed indoor and close to living spaces, similar to the traditional gas boilers or built-in household appliances, present the high efficiency proper of the Stirling thermodynamic cycle (the working fluids: air, azote, helium or hydrogen), are quietly running with up to 20% modulation ratios and, in virtue of the external combustion, are safe due to less emissions and have the possibility of being fed by high temperature thermal wastes. On the energy flow diagram reported in Fig. 19, 1 kW electricity production and cogenerated heat with a 7 kW natural gas supply is shown – however, according to the use side energy demand, it is possible to provide a supplementary thermal load by means of an auxiliary burner.

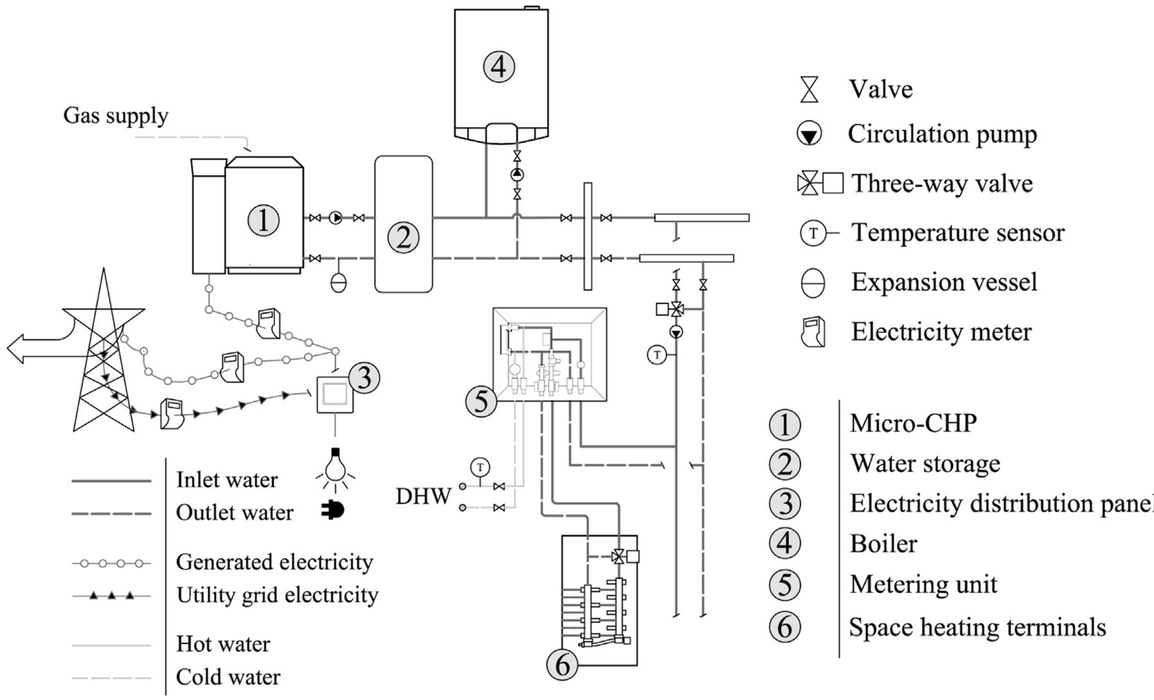


Fig. 18. Schematic of an integrated energy system providing space heating, DHW and electricity in a multi-family residential building.

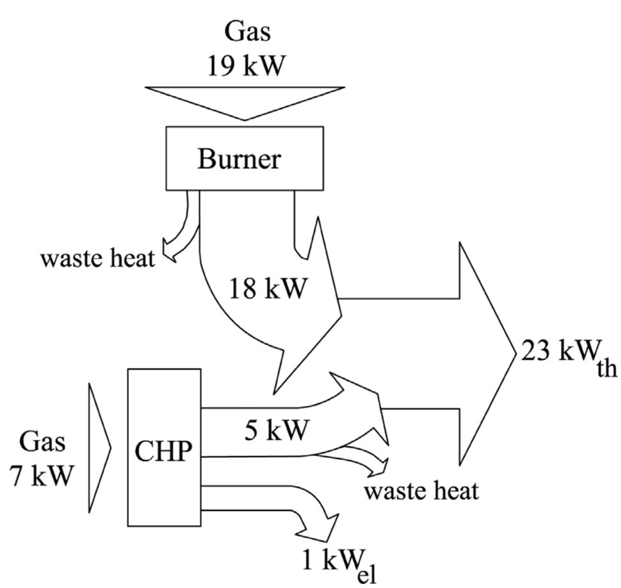


Fig. 19. Flow diagram for a Stirling engine microcogenerator–boiler system.

4.3. Dish Stirling solar based cogeneration system

Cogeneration convenience over separate electric and thermal production systems is maximised using renewable energy sources for on-site coverage of the energy demand whilst delivering the energy surplus produced to the utility [106]. As proven by a growing literature on this subject, efforts were directed on developing and refining solar energy based cogeneration technologies, in particular in geographical areas afflicted by water scarcity. Cogeneration solar thermal power plants, using point-focusing solar receivers equipped with a tracking system, represent a system potentially well-suited to meet the energy demand of small communities (e.g., 100 kW_{el}/700 kW_{th} capacities) [119,120].

On a smaller scale, one of the most renowned technologies based on solar concentration (tracing back to the 1800 s), is the Dish/Stirling thermodynamic cogeneration system, which provides thermal energy (for space heating and DHW) and electricity in AC – no power inverter is needed to feed the electric-utility grid – covering up to 3 kW_{th} and 1 kW_{el} peaks. In particular, converting solar energy directly into useful power for grid connexion and occupant use is strategic in order to reduce costs and improve the system reliability [121].

A Dish/Stirling cogeneration system comprises a concentrator (dish), a receiver, a Stirling engine and ancillary equipment (controls, cooling and storage system). The solar dish collector – a paraboloid of revolution with reflective coating – tracks the sun conveying the incoming direct insolation to a central focus point; the receiver stores the energy which activates the Stirling cycle by heating a high-pressure working fluid such as helium or hydrogen. Solar-dish tracking and engine operation is coordinated by controllers placed on the concentrator; furthermore, sensors that monitor specific boundary conditions such as wind speed or precipitations, allow to “close” on itself the whole system in a security position. An energy optimisation technique to investigate the optimal performance of a focusing collector-driven can be found in [122]. Considering a solar radiation in the order of 1600 kWh/m^2, thermal and electrical efficiencies amount respectively to roughly 40% and 13%, for an overall conversion efficiency close to 50% [123].

Dish/Stirling engine systems offer plenty of potential for further exploitation of solar energy. Modular design, ease of disassembly, quiet running and low emissions weigh up a strong visual impact, high investment costs and still a lack of operation data.

4.4. Microturbine based CHP

Since the 1950s large and medium-scale gas-fired turbines have been used to produce electricity; recently, technological innovation led to the introduction of smaller size turbines known as micro-turbines [124]. Micro CHP turbine systems allow to

recover excess thermal energy for space and domestic water heating. A compressor operates on the outside air, which is thus preheated in a heat exchanger and further integrated within a combustion chamber fired with natural gas – or, alternatively, liquefied petroleum gas, biogas, propane, gasoil or kerosene (in particular, biogas recovered from animal waste can be used with a view to minimising natural resource consumption). Exhaust gases are then expanded through the microturbine and used to preheat the air from the compressor before being introduced in the combustion chamber. Finally, a quota of the thermal energy from the exhaust gases is transferred to the working fluid operative in the heat exchanger for heat recovery [125]. Systems operating with heat recovery at full loads can combine 40–50% thermal efficiencies with around 30% electrical efficiency ratios, reaching global cogeneration efficiencies close to 80%. Below full loads, thermal efficiencies increase while electrical efficiencies show a downward trend.

Research converged mostly in analysing 30–100 kW generators [126], however also smaller generators – in the range 2–5 kW – have been investigated [127] in virtue of benefits such as limited emissions in contrast with conventional power plants [128,129], high energy efficiency ratios, light-weight and expected lifespan – about 45,000 h [130]. Due to their small capacities, microturbines allow to dispose off onsite electricity close to the point of use reducing dependence on electrical energy from the grid [124] and appear particularly well-suited as local electricity generators integrated into microgrids [126]. An insight into the state-of-the-art of this technology is available in [131,132] and in [130] with an emphasis on barriers and possible advancements in hybrid systems integrating microturbines. Hybridisation of turbines with other technologies such as solid oxide fuel cells [133] appears promising with a view to reaching higher energy conversion efficiencies.

However, even though significant upgrades over the last years enhanced microturbines technology, their adoption in residential buildings is currently quite uncommon since relatively recent.

5. Integrated systems for ventilation, space heating, cooling and DHW

The preponderant quota of a ZEB energy demand for air conditioning is attributed to the ventilation; therefore, instead of relying on natural ventilation which is strongly influenced by the occupant behaviour, an energy system for a ZEB ought to be equipped with a mechanical ventilation (MV) system in order to control the ventilation flow rate and especially to recover the ventilation heat losses. This aspect is strategic since it allows residential buildings to reach higher energy performances. At the same time, mechanical ventilation systems represent an effective means of controlling indoor pollutants concentrations and preventing indoor air quality deterioration [134]. Recently, there has been a spread of technologies for the mechanical ventilation (heat recovery, heating, cooling and dehumidification), which are emblematic of the on-going shift towards integrated systems, in particular within the high performing buildings.

Energy-efficient technologies for thermal energy recovery play a central role in reducing the overall building energy demand. Heat recovery from ventilation air is the most influent factor decreasing the ventilation energy demand of a mechanical ventilated building [135], which can increase up to 50% of the household electrical consumptions [136]. In comparison with a traditional exhaust ventilation system, a heat recovery system with 80% recovery efficiency has been proven to perform up to 67% global energy savings, decreased to 41% for a 60% energy efficient heat recovery system [137]. A literature review on heat recovery systems integrated with mechanical ventilation is available in [138].

5.1. MV units

Integrated systems for MV can be distinguished between decentralised and centralised units.

The first one consists of wall, ceiling or window-systems connecting the indoor and outdoor environments (for example through a hole in the wall), and are placed in each thermal zone. A decentralised air handling terminal placed in correspondence of the external wall to provide “on demand” ventilation in each room is described in [139]. Decentralised units can also be integrated on the window frame. These units operate with 15–30 m^3/h to 400 m^3/h air flow rates and are equipped with static or enthalpy heat exchangers. A model to assess the efficiency of decentralised units with supply and exhaust fans and heat exchanger can be found in [140].

Decentralised system with heat recovery can be adopted also for building retrofitting. However, even though high energy savings can be obtained, the integration of a MV system within an existing building not originally conceived for this purpose is problematic, and noise generation and negative pressure within the apartments (often a consequence of a low-quality design) are the main potential drawbacks of this solution [141].

Concerning the centralised configuration, a dual duct ventilation system is placed along all the buildings, with a central unit providing heat recovery, heating and optional cooling. Ducts can be flexible or rigid and ceiling mounted or floor embedded, depending on the building construction type. The ventilation unit can be installed on ceiling, in the bathroom or next to the kitchen hood (however in some countries like Italy, exhaust ventilation air cannot be mixed with exhaust gases from gas cookers [142]).

The air handling unit can be provided with a flat plate static, rotatory or thermodynamic heat exchanger for heat recovery. The parameter used for rating the heat transfer effectiveness between inlet and outlet air is the efficiency.

The parameter used to assess the fan efficiency is referred to as specific power input (SPI), the ratio of the effective power input and air flow rate in watt per cubic metre of air volume flow in one operating hour. It is fixed to 0.35 W/m^3h for balanced ventilation units and 0.23 W/m^3h for unidirectional ventilation units by the draft of the European regulation on ventilation units [143]; an insight into the repercussions of the Ecodesign European Directive [144] on residential ventilation units is carried out in [145].

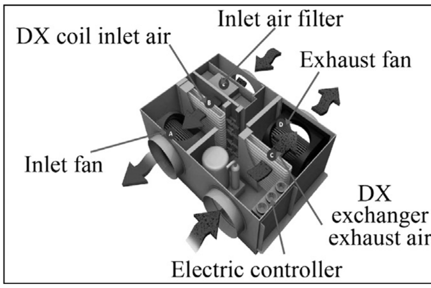
Compared to a static one, a rotatory heat exchanger provides higher heat recovery and partly humidifies the inlet air during winter (avoiding indoor air to get too dry); in rigorous climates freezing is prevented by reducing the air flow rate in response to cold outdoor air and high indoor relative humidity.

Often, also the air handling units are provided with a supplementary electric resistance for post-heating in winter conditions and with a heat exchanger bypass useful to avoid air heating in summer conditions.

A water coil can also be installed on the primary air duct (Ø 100–400) to cool (or heat) the inlet air. This two pipe coil is placed after the heat exchanger and provides air dehumidification and cooling in summer (fed by chilled water) or air heating in winter (fed by hot water) when the heat exchanger and the electric resistance heater within the ventilation units are not enough to cover the heating demand. In cooling mode, this solution may be necessary for air dehumidification, allowing the operation of radiant panels and reducing the air temperature, guaranteeing a correct air supply within the zones. In order to regulate the supply air temperature, the coil is equipped with controllers, sensors, actuators and protection valves.

5.2. Thermodynamic heat recovery unit

Thermodynamic-based heat recovery ventilation units appear suitable for the residential market. Relatively recent,



Air flow rate	54	l/s
Sound pressure level	39	dB(A)
SPACE HEATING		
Thermal capacity	1.82	kW
Compressors load	0.38	kW_{el}
Total load	0.42	kW_{el}
COP	4.33	
SPACE COOLING		
Thermal capacity	1.56	kW
Compressors load	0.48	kW_{el}
Total load	0.52	kW_{el}
EER	3	

Fig. 20. Centralised ventilation unit with thermodynamic heat recovery and operating characteristic.

thermodynamic heat recovery units operate between inlet and exhaust air as pictured in Fig. 20, where also the operating characteristics are provided. Since heat transfer is higher in comparison with the heat flux treated by the static or rotatory heat exchanger, they also allow to partly cover the space heating load. A micro heat pump, usually equipped with scroll compressor and with R-410A refrigerant, works between the two coils: in winter mode, a coil is condensing in the outside air flow, preventively filtered, and the other coil is evaporating in the exhaust air (the reverse cycle in Summer mode). The parameter used to assess the heat transfer efficiency between outlet and inlet air is actually the air-to-air micro heat pump COP (EER in cooling mode).

In mid-seasons, the system operates in free-cooling mode. Above the temperature where the outside air temperature matches the set point temperature, and up to the temperature where air cooling is required, the unit is set in free-cooling mode (or, more appropriately, works as a mere fan, without operating the heat pump); when the outside air temperature rises, the supply air temperature is reduced. Under heating conditions, the supply air temperature rises with higher outside air temperatures, in virtue of a greater heat exchange between the two air flows, until the compressor is set on an on/off operating schedule to prevent excessive inlet air overheating. The air flow rates are typically fixed and well-balanced; otherwise, below – 5 °C and above 30 °C outside air temperatures, the unit operation becomes problematic (the former since the source temperature is too low, the latter for a limited dehumidification capacity) and air flows need to be modulated to run with an inlet temperature below the set point in the cold zone and with less dehumidification in the warm zone.

More generally, according to Bo et al. [146], thermodynamic heat exchangers allow also the heating and cooling capacities of the energy system to be reduced (and sometimes their absence, as in a Passivhaus), the hydronic circuit impact to be reduced and hot/chilled water to be produced at more convenient low thermal levels.

Lastly, it is worth noting that these ventilation units are entirely fed by electricity, consequently connexions and system operation are simplified.

5.3. Compact HVAC

What appears a logical consequence of the centralised ventilation units is the compact HVAC for Passivhouses, designed by the Freiburg Fraunhofer Institute [147] and currently adopted in different versions by several manufacturers. The Passivhaus Programme exploits low capacity compact HVAC units to cover a limited space heating demand, below 15 kWh/(m^2 year) [148]. The Passivhaus Planning Package software [149] reports the expected ventilation rates – lowered under winter conditions in order to provide a suitable internal humidity [150,151] – which should be monitored during occupancy to avoid potential deviations from the benchmark.

Fig. 21 provides a working schematic of a compact HVAC, which supplies ventilation and DHW production (in a ZEB, at least in the building living spaces, it can also cover the energy demand for space heating). After flowing in an optional subsoil heat exchanger, fresh air circulates within an air-to-air flat plate heat exchanger and is provided to the thermal zones. Meanwhile, return-air exchanges heat with the supply air and is then exhausted. A micro heat pump operates between supply and exhaust air flows for possible supply air post-heating, in analogy with a thermodynamic heat exchanger. In particular, the heat pump, evaporating in the exhaust air –whose temperature under winter conditions would be favourably higher than the outside air temperature – is equipped with two condensers, a DX coil on the supply air and a heat exchanger placed within the DHW thermal storage, with optional solar thermal integration and electrical resistance for back up heating. The main strength of this system is its packaged configuration, where air is exploited both as heating fluid and heat pump thermal energy source.

Different configurations of compact HVAC are currently available in the market. Fig. 22 shows a system that instead of using a supply air-DX coil of a heat pump, adopts a double coil heat exchanger working with an intermediate fluid which draws off heat from the hot water storage to integrate, if necessary, the supply air temperature.

A further compact HVAC system combines an exhaust air/water heat pump with a system for domestic ventilation with heat recovery higher than 80%, DHW production (with 250 l storage capacity) and optional solar integration (Fig. 23). This system is already equipped with apposite connexions for hydraulic heating systems, resulting tailored for hydronic circuits: the heating capacity amounts to 7.3 kW, in addition to 2.3 kW at the “air side”. The ventilation unit operates with an air volume flow from 20 to 70 l/s, and the latent heat from the filtered extract air removed from bathrooms and kitchens is used to heat domestic water or the incoming air supply. A control unit coordinates the operation of the compact system according to different boundary conditions; furthermore, peak loads can be covered by a backup electric heater rod operating as second heat source at three different stages (2–4–6 kW).

In analogy with the compact HVAC for Passivhouses principle, but considered as a stand-alone system, thermodynamic heat recovery can be carried out on the exhaust ventilation air. This system consists of a heat pump operative between the exhaust air (coil at the top of the storage) and an appropriate DHW storage (coil at the bottom of the storage). The appliance is equipped with a 200 l volume and reaches a 2.5 COP when water is heated from 15 °C to 50 °C with 200 m^3/h air flow rate and 15 °C air temperature. The correct air flows balance is the main drawback of this system.

6. Discussion

Set against the requirements of the EPBD recast, integrated systems currently mark a strong step forward into next targets in energy savings for the transition to nNZEB in Europe by 2020. Increasing interest is thus being addressed to multi energy systems for space heating, cooling, ventilation, air conditioning and DHW production. Understanding the various peculiarities of

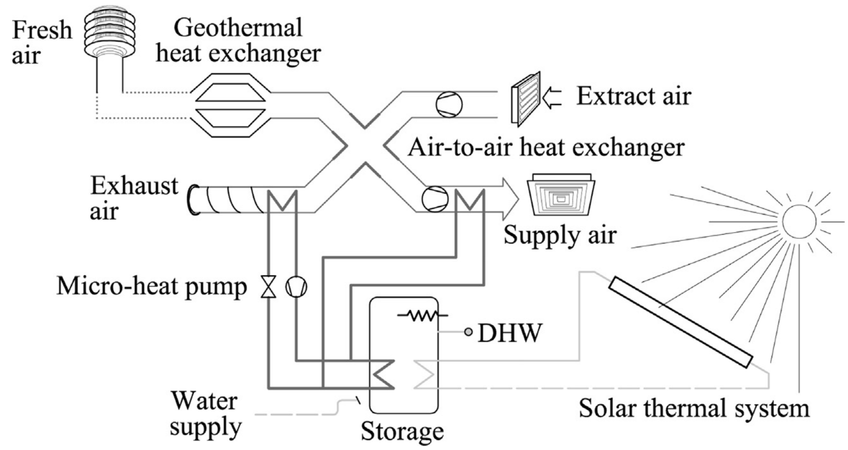


Fig. 21. Schematic of a compact HVAC for Passivhaus equipped with a supply air-DX coil.

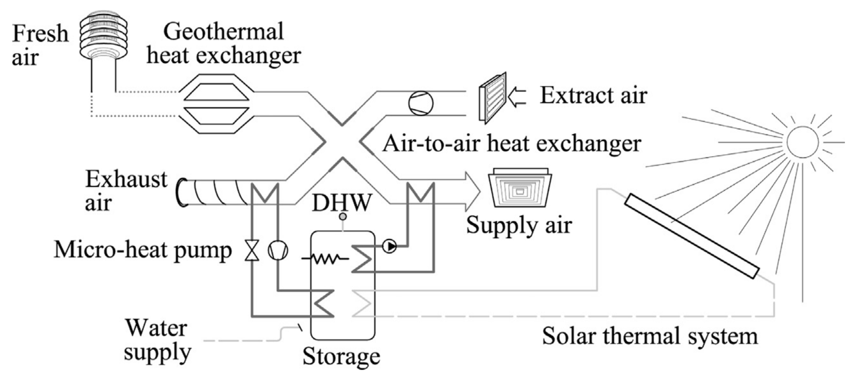


Fig. 22. Schematic of a compact HVAC for Passivhaus equipped with a double heat exchange coil.

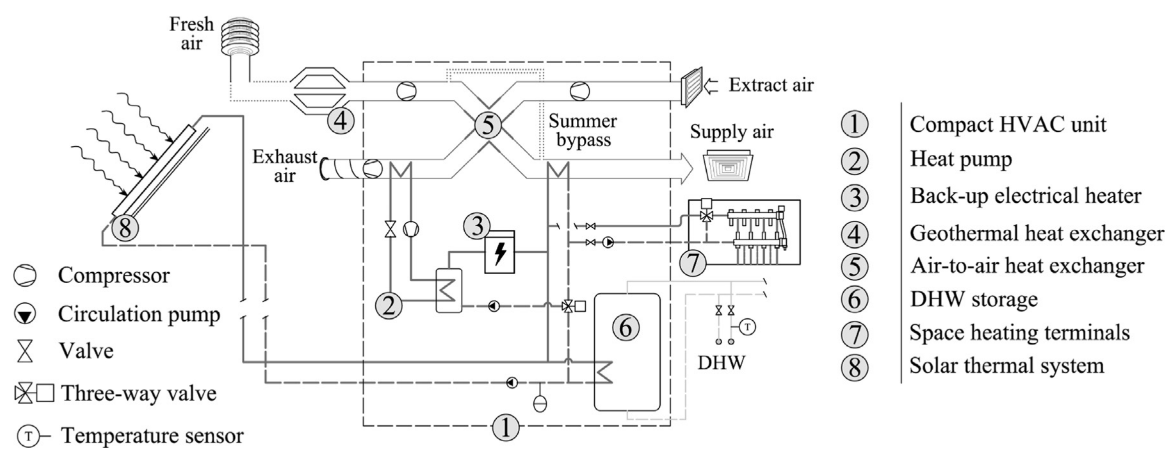


Fig. 23. Compact HVAC unit for hydronic circuits.

such systems is necessary in order to perform a correct design and operation and to promote the theoretical and practical development of these systems.

The integrated energy systems reviewed in this manuscript are distinguished by a variety of characteristics which influence their suitability for particular applications, context or situations. Table 2 compares the energy systems investigated according to the energy source exploited (solar, gas, biomass, grid electricity), the energy use served (space heating & cooling, DHW, plug loads & lighting, ventilation & air handling), capacities and efficiencies, strengths and advantages, weaknesses and drawbacks.

Overcoming the intrinsic limits characteristic of separate production energy systems – taken separately, the room for further performance improvement is limited – is the rationale behind the integrated set-up condensing boiler-heat pump. Small size condensing gas boilers are characterised by a high thermal output, above the unit, optimal for low-temperature space heating, but rely on fossil fuel consumption. Reversible heat pumps are best suited for balanced heating and cooling loads coverage, since a high indoor-outdoor ΔT significantly increases the external energy quota required to reverse spontaneous heat flow. The coupling with a small-size boiler activated above a specific threshold temperature where heat pump is no more convenient addresses this problematic maximising the total energy efficiency of the system. In solar-rich countries, a solar thermal integration is desirable since both technologies can be easily attached to a solar

Table 2
Peculiarities, strengths, advantages, weaknesses and drawbacks of the integrated production systems under review.

Energy system	Energy input	Energy output	Heating/Cooling/ Electricity Capacity	Design Efficiency	Strengths and advantages	Weaknesses and drawbacks
Small size gas boiler	Gas, (solar)	Space heating, DHW	Up to 24 kW	> 1.00	– Low-temperature space heating (e.g., in-floor radiant panels) – Optimal performances at low return temperatures [15] – Minor ecological footprint in terms of internal and external costs compared to biomass-based energy systems [18] – Instantaneous DHW production or through integrated storage volume (from 50 l) – Integration with solar thermal	– Non-renewable energy source – High-temperature space heating (e.g., radiators) – Variation of the performance according to the load pattern [19]
Firewood boiler based system	Biomass	Space heating, DHW	15–60 kW	0.92–0.95	– Carbon neutral [20] – Lower nitrogen oxide and sulphur dioxides emissions compared to oil or coal combustion [21] – High combustion temperature maintained during the entire burning process [22]	– Manual feeding – Incomplete combustion of organic material can be reduced but not eliminated – Unstable burning process, variable emission factors [24] – High moisture content of the firewood – Mismatch between real and theoretical supply air volume – air excess volume should be accurately sized [21] – Thermal energy storage tanks connected to the central heating system might be needed to prevent overheating [23]
Pellet boiler	Biomass, (solar)	Space heating, DHW	2.9–26 kW	0.92	– Moisture content two times lower than firewood (less drying required) [25] – Steady emission factors [24] – Facilitated storage and operations (automatic feeding) [26] – Low GHGE [26] – Integration with solar thermal [36]: 25% reduction in pellet consumption and 44% reduction in CO emissions [37]	– Pollutants from pellet combustion, including CO and C_xH_y [28], dust [29], [30], SO_x, NO_x [31],[32] and PM [34] – Lower efficiencies and higher emissions at reduced loads [33] – Unsustainable pressure for biomass provision might bring to woodland degradation especially in developing countries [35]
Pellet room heater	Biomass, (solar)	Space heating, DHW	1.5–12 kW	0.80–0.90	– Maintenance of high combustion temperatures and maximisation of turbulent gaseous mixing [40] – Operations can be regulated remotely by means of dedicated apps – Integration with water heat exchangers for in-floor radiant heating or DHW production – Integration with solar thermal – Integration with back boilers – Reduction of particulate emission with optimised condensing heat exchangers [44]	– Dust is linked to PM and polycyclic aromatic hydrocarbons emissions [41] – Steady state-based standard measurements can significantly diverge from emissions under real operations [42] – High noise levels in living spaces – Frequent cleaning for ash removal – Relief valves should be installed in hydronic set-up to prevent risks of explosions
Slow heat release stove	Biomass, (solar)	Space heating, DHW	1.6 kW (mean output over 10 h)	0.83–0.86	– Low direct heat output prevents space overheating – Thermal storage capacity stabilises ambient temperatures for several hours after combustion [45] – Top wood burning minimises emissions – Low surface temperature of the stove reduces dust circulation – Salt hydrate based thermal storage further extends the slow heat release – Integration with water heat exchangers for space heating – chimney outlets and additional heating systems not needed	– Natural stone storages need a relatively high mass and volume – Stored heat might be undesirable in case of sudden meteorological changes leading to overheating – Relief valves should be installed in hydronic set-up to prevent risks of explosions – Low efficiency of the prefabricated double-walled heat storages [46] – Experience-based, lack of theoretical studies [46]

Table 2 (*continued*)

Energy system	Energy input	Energy output	Heating/Cooling/ Electricity Capacity	Design Efficiency	Strengths and advantages	Weaknesses and drawbacks
SAHP	Electricity from grid, solar	Space heating, DHW, (space cooling)	8–16 kW	3.9–4.2 COP (35 °C water supply temperature) 4.20–4.50 EER (18 °C water supply temperature)	– Substantial body of literature on SAHP modelling, designing and testing e.g., [13,51–53] – Appropriate for detached houses – Maximisation of renewable energy exploitation – Variety of available technologies – Evaporator–collector efficiencies are higher than the one of conventional collectors [50] – Potentially closed cycle if electricity is provided by PV	– Centralised storage and integrations are needed in multi-family residential buildings – Balanced distribution of the heating and cooling loads is needed over the year (i.e. not suitable for excessively warm/cold climates) [56]
Condensing boiler-heat pump	Electricity from grid, solar, gas	Space heating, DHW, (space cooling)	3.3–33 kW condensing boiler; 6–8 kW heat pump	Up to 1.27	– Upgrading of the heat pump performances [54] (respective benefits combined in one energy system) – Maximisation of the energy system total efficiency – Flexibility: peak loads can be covered by the condensing boiler above the cut-off temperature; integrated or separate set-up; different heat pumps types are suitable (also absorption heat pumps) – Potentially closed cycle if integrated with PV	– Complex integrated design – Balanced distribution of the heating/ cooling loads needed over the year (i. e. not suitable for excessively warm/ cold climates) [56]
Zeolite based integrated system	Gas, (solar)	Space heating, DHW	10–15 kW	Up to 1.28	– Complementarity with heat pump cycles, high thermal storage capacity over a multitude of adsorption/ desorption phases [59] – Non-toxic and non-flammable – Suitable for low-temperature space heating – Economic competitiveness [64], effective operation, extended operating life, quiet running, lack of hazardous materials and moving parts [65] – Integration with solar thermal	– A niche technology – Heat and mass transfer problems, leakages, relatively low COP [65,66]
Multi-energy storage	Gas, (solar)	Space heating, DHW	18–30 kW	0.975	– Currently seasonal thermal storage in the form of sensible heat is more viable than in the form of latent heat [73] – Provision of hot water at different thermal levels – Integration with solar thermal – Legionella can be prevented by running DHW in a dedicated pipe system within a thermal energy storage – Unpressurised and direct drain-back solar thermal systems may avoid antifreeze agents (but specific design conditions should be met)	– Complex design – effective thermal stratification in the storage medium is needed to improve heat transfer when the storage is charged/ discharged [73] and solar thermal circuit efficiency [74]. Heat exchangers should be placed according to operating temperature required by uses – Dedicated technologies (e.g., diaphragms, stratifiers) preventing mixing within the storage should be used [76–78]
Reversible heat pump	Electricity from grid, (solar)	Space heating, DHW, space cooling	5–20 kW	5.70 SCOP (35 °C water supply temperature) 5.48 ESEER (18 °C water supply temperature) – Depending on the	– Widely used solution for space heating and cooling – Recently also DHW can be produced with heat recovery – Integration with solar thermal – Potentially closed cycle if integrated with PV – Optimal performance at lower loads – Hot/chilled water and DHW production can be combined in total heat recovery system	– Dependence on the outdoor-indoor temperature gradient – Potential mismatch between expected and real operating conditions (evaporator/condenser source side temperature, ΔT) – Lack of data from manufacturers on operating conditions different from reference points – Additional thermal resistance may be needed for DHW production for

Table 2 (*continued*)

Energy system	Energy input	Energy output	Heating/Cooling/ Electricity Capacity	Design Efficiency	Strengths and advantages	Weaknesses and drawbacks
				design conditions		air-source heat pumps – Part load performances may show significant differences
VRF/VRV	Electricity from grid, (solar)	Space heating, DHW, space cooling	From 12.5 kW up (heating) from 1.2 kW up (cooling)	2.5–5 COP depending on design conditions	– Energy performance and cost effectiveness – The indoor unit refrigerant flow rate can be calibrated on the cooling loads [81] – Integration in hydronic systems through refrigerant-water heat exchangers [86] – Hot/chilled water can be produced at the same time through external units with heat recovery – Heat recovery from thermal zones under space cooling for the integration of hot water production – Integration with solar thermal	– Limited hot water thermal level (45 °C) (but up to 70 °C hot water can be produced by partialising the thermal lift) – Difficulty of customising energy simulation software tools for the long term energy performance assessment of such systems [85] – Superheats in indoor units and compressor speed should be carefully designed [83]
GEHP	Gas, (solar)	Space heating, DHW, space cooling	25–80 kW	1.50 (Heating) 1.40 (Cooling)	– Natural gas substitutes electricity – avoided conversions: fuel-electricity (power plant) and electricity-mechanical energy (heat pump) – Free DHW production – Heat recovery from the engine cooling and from exhaust used for refrigerant evaporation (heating mode) and DHW (cooling mode) – High primary energy ratio [90],[91] – Hybridisation with other technologies and systems has the potential to further increase the overall energy performance [92,93]	– A niche technology – Not suitable for small sizes (e.g., single family houses) – Parasitic power consumption – Further improvement in control systems and equipment are necessary [87] – Total heat recovery-based DHW production still not reliable due to operation at part loads and in summer and mid-seasons
GAHP	Gas, (solar)	Space heating, DHW, space cooling	25–80 kW	1.50–1.70 GUE	– Exploitation of low valued energy – High energy savings and low GHGE [95] – No chlorofluorocarbon refrigerants [94] – Integration of gas-fired condensing boiler to rise hot water supply temperature up to 80 °C – DHW by means of condensing heat recovery – High condensing heat recovery due to low cooling energy efficiency ratio – Hybridisation with other technologies and systems (e.g., solar thermal and geothermal) can further improve the overall energy performance [97]	– Not suitable for small sizes (e.g., single-family houses), oversizing might increase energy consumption and reduce GAHP overall effectiveness – R elatively lower efficiencies for air evaporating heat pumps and DHW production at high thermal levels – Total heat recovery-based DHW production still not reliable due to operation at part loads and in summer and mid-seasons
Internal combustion engine CHP	Gas, (solar)	Plug loads & lighting, space heating, DHW	12.5 kW_{th} 5.5 kW_{el}	0.20–0.30 Electrical 0.60–0.70 Thermal	– Well-established technology – Most viable CHP for residential applications [109] – A variety of energy sources can be used [110] – Latent heat recovery from exhaust – The hot water return temperature can be decreased to 35 °C by installing a dedicated heat exchanger for exhaust gases condensation	– Low electrical efficiencies characteristic of small size internal combustion gas engines – Economic feasibility directly linked with feed-in tariff and running hours
Stirling engine based CHP	Gas, (solar)	Plug loads & lighting, space heating, DHW	1 kW_{el} 6 kW_{th} + 6–20 kW_{th} additional	0.15 Electrical 0.80 Thermal 0.98 Additional	– Cutting-edge CHP technology [116], [117] – 5000–8000 running hours without significant need for mechanical maintenance (< 20 kW Stirling engines) [105] – Quiet running	– Parasitic power consumption (exhaust from the engine) – An auxiliary burner might be needed to cover peak loads

Table 2 (*continued*)

Energy system	Energy input	Energy output	Heating/Cooling/ Electricity Capacity	Design Efficiency	Strengths and advantages	Weaknesses and drawbacks
					– Up to 20% modulation ratios – Safety (external combustion) – High temperature thermal waste can be used as energy source	
Dish stirling	Gas, solar	Plug loads & lighting, space heating, DHW	3 kW_{th} 1 kW_{el}	0.13 Electrical 0.40 Thermal	– One of the most well-known solar concentration based technologies – On-site renewable energy exploitation maximises CHP effectiveness against separate electricity and thermal energy production systems [106] – Large scale solar thermal power plants are potentially suitable to cover small communities' energy needs (e.g., 100 kW_{el}/700 kW_{th}) [119,120] – Energy surplus exported to the grid valorised by dedicated incentives – AC electricity – no power inverter required, reduction of grid connexion costs, system reliability [121] – Modular design, easily (dis) assembled, quiet running, effective solar tracking system	– Abundant solar energy radiation constantly distributed over the year is essential – Visual impact – Investment costs – Adverse weather conditions might compromise solar-dish tracking and engine operations (but a security position is automatically set-up) – Still scarce operation data
Microturbine based CHP	Gas, (solar)	Plug loads & lighting, space heating, DHW	25–500 kW	0.30 Electrical 0.40–0.50 Thermal	– Technological innovation is progressively increasing the effectiveness of small size turbines – Biogas from manure can be used for combustion – Heat recovery from exhaust [125] – Limited emissions compared to conventional power plants [128,129] – Light weight – 45,000 h Operating lifespan [130] – Onsite electricity provision close to the point of use [124] – Integration with microgrids [126] – Hybridisation with solid oxide fuel cells systems can further improve energy conversion efficiencies [133]	– Still a niche technology, unusual for residential applications – Literature mostly on intermediate/ large size generators (30–100 kW) [126]
MV unit	Electricity from grid	Ventilation & air handling, (space cooling)	15–400 m^3/h air flow rates (decentralised) 140–350 m^3/h air flow rates (centralised)	0.80–0.90 Heat recovery efficiency (decentralised) Up to 0.90 heat recovery efficiency (centralised)	– Decentralised MV: 'on demand' ventilation in each room [139] – Architectural integration – decentralised units can be contained within the window frame – Heat recovery, especially with rotatory heat exchanger – High energy savings, especially in retrofitted buildings [141] – Centralised MV: ductwork can be adjusted to the building construction type – Water coils can be integrated for air heating in winter and air dehumidification and cooling in summer	– Installation in existing buildings: noise generation and negative pressure within the zones might rise [141] – A supplementary electrical resistance (post-heating in winter) and a heat exchanger bypass (to avoid air heating in summer) necessary
Compact HVAC	Electricity from grid, solar	Space heating, DHW, space cooling, ventilation & air handling	Up to 7.3 kW_{th} hydronic circuit + 2.3 kW_{th} air side	> 0.80 Heat recovery efficiency	– Optimised for low energy housing – Variety of versions are available from an increasing number of manufacturers – Packaged configuration: air exploited as working fluid and heat pump's thermal energy source – Integration with solar thermal – > 80% heat recovery from bathrooms' and kitchens' extract air – Pre-set connexions for hydronic circuits	– Monitoring of ventilation rates ought to be conducted during occupancy – Electrical resistance for back up heating as second heat source (2–4–6 kW) – Limited data on the variable energy efficiency of the heat pump sub-system – Difficulty of conducting long term energy performance assessment in standard dynamic simulation software tools (need of customised models)

thermal circuit. Solar assisted heat pumps are particularly recommendable for detached houses – in multi-family residential buildings, the need of centralised or individual thermal integrations would decrease their convenience. In addition, PV panels could be added to cover the compressor electricity demand, obtaining a stand-alone renewable energy based production system – this principle often recurs in passivhouses. GEHP and GAHP are considered a competitive alternative to electricity-driven heat pumps, especially in countries with high price of electricity. In addition to a high primary energy ratio, both solutions are distinguished by the possibility of producing DHW from heat recovery. However, total heat recovery-based DHW production is still believed premature and operations at part loads should be carefully evaluated by means of dedicated simulations. Still niche technologies, GEHP and GAHP are limited to intermediate sizes (25–80 kW), and oversizing their capacity in smaller applications might undermine related efficiencies: their potential is better exploited at the multi-family household scale.

A further cutting-edge substitute to vapour compression heat pumps is constituted by thermal driven adsorption heat pumps based on zeolite as adsorbent, able to combine long-term effective operations with economic competitiveness and safety.

Particularly recommended for low temperature in-floor radiant heating with solar thermal integration, the main drawbacks of zeolite-based energy system are relatively lower COPs and heat and mass transfer problems.

Finally, VRF/VRV based systems should be taken into account in mixed-use buildings demanding at the same time hot and chilled water, with the possibility of exploiting thermal energy recovered from cooled thermal zones to integrate hot water production. The adoption of refrigerant-water heat exchangers would extend the applicability of this solution to low-temperature hydronic systems (unless cascade solutions are used, hot water production is limited to 45 °C).

Biomass-based energy systems are of particular interest in forested countries. Besides being carbon neutral, pollutants from incomplete combustion of organic products have been significantly reduced by new combustion techniques. The use of firewood might be arguable for a ZEB – firewood is increasingly substituted by pellets with lower moisture content, easier storage and operations and well-defined emission factors. Pellet boilers should be adopted in combination with solar thermal to obtain significant savings in pellet consumption and pollutant emissions. Pellets room heaters, optionally equipped with water heat exchangers for space heating or DHW production, would be best suited for low energy one-floor houses with an optimal design for heat transfer. Noise levels in living spaces and frequent cleaning operations are some of the practical drawbacks which however need to be taken into account.

Nevertheless, the most convenient biomass solution for a ZEB is based on slow heat release stoves exploiting the thermal capacity of PCM (salt hydrate) to maintain temperatures above 30 °C for several hours after charging, preventing overheating problems. However, few theoretical studies have been found in academic literature on this technology.

With regards to electricity needs, CHP based systems are attractive because of useful heat recovered from power generation. In general, CHP economic feasibility can be directly linked with national policy mechanisms incentivising electricity export to the grid. Internal combustion engine-based CHP, the longest established solution, is characterised by the typical low electricity generation efficiency of small size internal combustion gas engines. Likewise, small size microturbines present global cogeneration efficiencies low (70–80%). Stirling engine based CHP is favoured by higher efficiencies characteristic of the Stirling thermodynamic cycle, performing over an extended operating life without particular maintenance needs. In appropriate geographical contexts Stirling engines could be used in concentrated solar power systems tracking solar energy to generate electrical energy in alternating current. This solution is recommended for off-grid small communities more that at a single household scale; high investment costs should be borne and a non-negligible visual impact should be taken into account.

MV units represent a valid solution for ventilation and air conditioning. Depending on the building construction type, decentralised MV units, installed in wall, ceiling or windows, are recommended for on-demand ventilation to several thermal zones with different air changes, centralised units are recommended whereas a unique dual duct ventilation system best suits the system design.

Overall, the compact HVAC emerges among reviewed production systems for addressing energy needs for space heating & cooling, DHW, ventilation & air handling in one packaged set-up with a ‘water’ and ‘air’ side. Air can be used as thermal energy source for heat pump as well as working fluid, and heat is recovered with an 80% efficiency. The overall energy behaviour of this configuration should be monitored to prevent divergences from expected performance. Tailored for low energy housing, Compact HVAC combined with solar thermal has a potential to currently be one of the most appropriate integrated energy systems for a new construction ZEB.

However, it is not possible to assert *a priori* which multi-energy system among those reviewed should be selected for a specified ZEB. This will depend on the contingency of the design, the economic and environmental boundary conditions and cost optimal evaluations [152]. All these factors have to be taken into consideration – in an integrated way – from the first design phases.

7. Conclusions

This manuscript drew a picture of the most recent integrated HVAC and DHW production systems available for a ZEB. Literature review, peculiarities, strengths and weaknesses of different production systems have been pointed out. Multi-energy systems allow to overcome shortcomings proper of stand-alone (mono-carrier/mono-converter) energy systems being fed by a combination of various energy sources. The optimisation of their potential benefits however requires a whole building approach, implemented since the design concept stage, where all the design variables (technical, energy, financial, environmental) influencing one another are holistically harmonised to achieve an optimal, integrated result [153]. To do this, appropriate manufacturer data should be made available in order to perform, beginning from the design stage, detailed calculations of the energy performance of the system, like the ones reported in [154]. Currently, only synthetic data are usually available from manufacturers (e.g., design stage efficiencies, mean seasonal efficiencies calculated with reference conditions, etc.).

This seems the greatest challenge facing up multi-energy system in the future, whose spread on the market will depend on the capacity to minimise the mismatch between expected (design) and real (monitored) energy performances.

References

[1] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast); June 18, 2010.
[2] Fabrizio E, Corrado V, Filippi M. A model to design and optimize multi-energy systems in buildings at the design concept stage. Renew Energy 2010;35(3):644–55.

[3] Fabrizio E, Filippi M, Virgone J. An hourly modelling framework for the assessment of energy sources exploitation and energy converters selection and sizing in buildings. Energy Build 2009;41(10):1037–50.
[4] Manwell JF. Hybrid energy systems. In: Cleveland CJ, editor. Encyclopedia of energy, vol. 3. London: Elsevier; 2004. p. 215–29.
[5] Henning H-M. Solar assisted air conditioning of buildings – an overview. Appl Therm Eng 2007;27(10):1734–49.
[6] Balghouthi M, Chahbani MH, Guizani A. Feasibility of solar absorption air conditioning in Tunisia. Build Environ 2008;43(9):1459–70.
[7] Bakker M, Zondag HA, Elswijk MJ, Strootman KJ, Jong MJM. Performance and costs of a roof-sized PV/thermal array combined with a ground coupled heat pump. Sol Energy 2005;78(2):331–9.
[8] Iqbal MT. Modeling and control of a wind fuel cell hybrid energy system. Renew Energy 2003;28(2):223–37.
[9] Dufo-López R, Bernal-Augustín JL, Contreras J. Optimization of control strategies for stand-alone renewable energy systems with hydrogen storage. Renew Energy 2007;32(7):1102–26.
[10] Beccali M, Brunone S, Cellura M, Franzitta V. Energy, economic and environmental analysis on RET-hydrogen systems in residential buildings. Renew Energy 2008;33(3):366–82.
[11] Nelson DB, Nehrir MH, Wang C. Unit sizing and cost analysis of stand-alone hybrid wind/PV/fuel cell power generation systems. Renew Energy 2006;31(10):1641–56.
[12] Liu XH, Geng KC, Lin BR, Jiang Y. Combined cogeneration and liquid-dessicant system applied in a demonstration building. Energy Build 2004;36:945–53.
[13] Trillat-Berdal V, Souyri B, Achard G. Coupling of geothermal heat pumps with thermal solar collectors. Appl Therm Eng 2007;27:1750–5.
[14] Sontag R, Lange A. Cost effectiveness of decentralized energy supply systems taking solar and wind utilization plants into account. Renew Energy 2003;28(12):1865–80.
[15] Lazzarin R. Condensing boilers in buildings and plants refurbishment. Energy Build 2012;47:61–7.
[16] Saidur R, Abdelaziz EA, Demirbas A, Hossain MS, Mekhilef S. A review on biomass as a fuel for boilers. Renew Sustain Energy Rev 2011;15:2262–89.
[17] Hepbasli A. Low exergy (LowEx) heating and cooling systems for sustainable buildings and societies. Renew Sustain Energy Rev 2012;16:73–104.
[18] Özdemir ED, Härdtlein M, Jenssen T, Zech D, Eltrop L. A confusion of tongues or the art of aggregating indicators—reflections on four projective methodologies on sustainability measurement. Renew Sustain Energy Rev 2011;15:2385–96.
[19] Lazzarin R.. Le caldaie a condensazione nella ristrutturazione di edifici e impianti [Condensing boilers in buildings and energy systems retrofitting]. In: Proceedings of the AiCARR conference innovazione tecnologica nella climatizzazione degli edifici nuovi e ristrutturati [Technological innovation for air conditioning in new and renovated buildings]. Padova, Italy; June 16, 2011. p. 17–33 [Italian].
[20] Strehler A. Technologies of wood combustion. Ecol Eng 2000;16:25–40.
[21] Gimbutaitė I, Venckus Z. Air pollution burning different kinds of wood in small power boilers. J Environmen Eng Landsc Manag 2008;16:97–103.
[22] Olsson M. Residential biomass combustion – emissions of organic compounds to air from wood pellets and other new alternatives. (Ph.d. thesis). Göteborg: Chalmers University of Technology; 2006.
[23] Hedman B, Näslund M, Marklund S. Emission of PCDD/F, PCB, and HCB from combustion of firewood and pellets in residential stoves and boilers. Environ Sci Technol 2006;40:4968–75.
[24] Jonsson A, Hillring B. Planning for increased bioenergy use—evaluating the impact on local air quality. Biomass Bioenergy 2006;30:543–54.
[25] Olsson M, Kjallstrand J, Petersson G. Specific chimney emissions and biofuel characteristics of softwood pellets for residential heating in Sweden. Biomass Bioenergy 2003;24:51–7.
[26] Pa A, Bi XT, Sokhansanj S. Evaluation of wood pellet application for residential heating in British Columbia based on a streamlined life cycle analysis. Biomass Bioenergy 2013;49:109–22.
[27] Rabaçal M, Fernandes U, Costa M. Combustion and emission characteristics of a domestic boiler fired with pellets of pine, industrial wood wastes and peach stones. Renew Energy 2013;51:220–6.
[28] Luque R, Herrero-Davila H, Campelo JM, Clark JH, Hidalgo JM, Luna D, et al. Biofuels: a technological perspective. Energy Environ Sci 2008;1:542–64.
[29] Obernberger I, Thek G. Physical characterisation and chemical composition of densified biomass fuels with regard to their combustion behaviour. Biomass Bioenergy 2004;27:653–69.
[30] Ryu C, Yang YB, Khor A, Yates NE, Sharifi VN, Swithenbank J. Effect of fuel properties on biomass combustion: part I. Experiments-fuel type equivalence ratio and particle size. Fuel 2006;85:1039–46.
[31] Verma VK, Bram S, Gauthier G, De Ruyck J. Evaluation of the performance of a multi-fuel domestic boiler with respect to the existing European standard and quality labels: part-1. Biomass Bioenerg 2010;35:80–9.
[32] Verma VK, Bram S, Gauthier G, De Ruyck J. Performance of a domestic pellet boiler as a function of operational loads: part-2. Biomass Bioenergy 2011;35:272–9.
[33] Verma VK, Bram S, Delattin F, De Ruyck J. Real life performance of domestic pellet boiler technologies as a function of operational loads: a case study of Belgium. Appl Energy 2013;101:357–62.
[34] Garcia-Maraver A, Zamorano M, Fernandes U, Rabaçal M, Costa M. Relationship between fuel quality and gaseous and particulate matter emissions in a domestic pellet-fired boiler. Fuel 2014;119:141–52.
[35] Matsika R, Erasmus BFN, Twine WC. Double jeopardy: the dichotomy of fuelwood use in rural South Africa. Energy Policy 2013;52:716–25.
[36] Žandeckis A, Timma L, Blumberga D, Rochas C, Rošā M. Solar and pellet combisystem for apartment buildings: heat losses and efficiency improvements of the pellet boiler. Appl Energy 2013;101:244–52.
[37] Persson T, Fiedler F, Rönnelid M, Bales C. Increasing efficiency and decreasing CO-emissions for a combined solar and wood pellet heating system for single family houses. In: Proceedings on USB of Pellets. Jönköping, Sweden; May 30–June 1, 2006.
[38] Fiedler F, Bales C, Persson T. Optimisation method for solar heating systems in combination with pellet boilers/stoves. Int J Green Energy 2007;4:325–37.
[39] Dieckmann J, McKenney K, Brodrick J. Warming up to pellet stoves. ASHRAE J 2010;52:82–3.
[40] Lee Y-W, Ryu C, Lee WJ, Park YK. Assessment of wood pellet combustion in a domestic stove. J Mater Cycles Waste Manag 2011;13:165–72.
[41] Riva G, Foppa Pedretti E, Toscano G, Duca D, Pizzi A. Determination of polycyclic aromatic hydrocarbons in domestic pellet stove emissions. Biomass Bioenergy 2011;35:4261–7.
[42] Toscano G, Duca D, Amato A, Pizzi A. Emission from realistic utilization of wood pellet stove. Energy 2014;68:644–50.
[43] Persson T, Nordlander S, Rönnelid M. Electrical savings by use of wood pellet stoves and solar heating systems in electrically heated single-family houses. Energy Build 2005;37:920–9.
[44] Gröhn A, Suonmaa V, Auvinen A, Lehtinen KEJ, Jokiniemi J. Reduction of fine particle emissions from wood combustion with optimized condensing heat exchangers. Environ Sci Technol 2009;43:6269–74.
[45] Georges L, Skreiberg O, Novakovic V. On the proper integration of wood stoves in passive houses under cold climates. Energy Build 2014;72:87–95.
[46] Buchner K, Hofbauer H. Optimisation of ceramic heat storage of stoves. Energy Build 2003;35:1121–8.
[47] Omojaro P, Breitkopf C. Direct expansion solar assisted heat pumps: a review of applications and recent research. Renew Sustain Energy Rev 2013;22:33–45.
[48] Kara O, Ulgen K, Hepbasli A. Exergetic assessment of direct-expansion solar-assisted heat pump systems: review and modeling. Renew Sustain Energy Rev 2008;12:1383–401.
[49] Ozgener O, Hepbasli A. A review on the energy and exergy analysis of solar assisted heat pump systems. Renew Sustain Energy Rev 2007;11:482–96.
[50] Amin ZM, Hawlader MNA. A review on solar assisted heat pump systems in Singapore. Renew Sustain Energy Rev 2013;26:286–93.
[51] Morgan RG. Solar assisted heat pump. Sol Energy 1982;28:129–35.
[52] Tleimat BW, Howe ED. A solar assisted heat pump system for heating and cooling residences. Sol Energy 1978;21:45–54.
[53] Svard CD, Mitchell JW, Beckman WA. Design procedure and application of solar-assisted series heat pump systems. J Sol Energy Eng 1981;103(2):135–43.
[54] Chua KJ, Chou SK, Yang WM. Advances in heat pump systems: a review. Appl Energy 2010;87:3611–24.
[55] Di Perna C., Giampieri M., Magri G. Analisi e sviluppo di un modello di calcolo del rendimento di produzione di sistemi di generazione ibridi per il riscaldamento ambienti [Analysis and development of a calculation model of hybrid systems' production efficiency for space heating]. In: Proceedings of the AiCARR conference innovazione tecnologica nella climatizzazione degli edifici nuovi e ristrutturati [Technological innovation for air conditioning in new and renovated buildings]. Padova, Italy; June 16, 2011. p. 177–89 [Italian].
[56] Zhai XQ, Qu M, Yu X, Yang Y, Wang RZ. A review for the applications and integrated approaches of ground-coupled heat pump systems. Renew Sustain Energy Rev 2011;15:3133–40.
[57] Taniguchi H, Kasahara K, Kudoh K, Kawamura K, Ohta J. Performance characteristics of heat pump-boiler system: part 1-performance analysis of the system. Transactions of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan; February 21, 1983. p. 31–41 [Japanese].
[58] Lazzarin R, Noro M. District heating and gas engine heat pump: economic analysis based on a case study. Appl Therm Eng 2006;26:193–9.
[59] Selvidge M, Miaoulis IN. Evaluation of reversible hydration reactions for use in thermal energy storage. Sol Energy 1990;44(3):173–8.
[60] Wang DC, Li YH, Li D, Xia YZ, Zhang JP. A review on adsorption refrigeration technology and adsorption deterioration in physical adsorption systems. Renew Sustain Energy Rev 2010;14:344–53.
[61] Jiangzhou S, Wang RZ, Lu YZ, Xu YX, Wu JY, Li ZH. Locomotive driver cabin adsorption air-conditioner. Renew Energy 2003;28:1659–70.
[62] Cacciola G, Restuccia G. Reversible adsorption heat pump: a thermodynamic model. Int J Refrig 1995;18(2):100–6.
[63] Cacciola G, Hajji A, Maggio G, Restuccia G. Dynamic simulation of a recuperative adsorption heat pump. Energy 1993;18(11):1125–37.
[64] Cacciola G, Restuccia G, Giordano N. Economic comparison between adsorption and compression heat pumps. Heat Recovery Syst CHP 1990;10(5–6):499–507.
[65] Demir H, Mobedi M, Ülkü S. A review on adsorption heat pump: problems and solutions. Renew Sustain Energy Rev 2008;12(9):2381–403.
[66] Restuccia G, Recupero V, Cacciola G, Rothmeyer M. Zeolite heat pump for domestic heating. Energy 1988;13(4):333–42.
[67] Parameshwaran R, Kalaiselvam S, Harikrishnan S, Elayaperumal A. Sustainable thermal energy storage technologies for buildings: a review. Renew Sustain Energy Rev 2012;16:2394–433.

[68] Stritih U, Osterman E, Evliya H, Butala V, Paksoy H. Exploiting solar energy potential through thermal energy storage in Slovenia and Turkey. Renew Sustain Energy Rev 2013;25:442–61.
[69] Sharma A, Tyagi VV, Chen CR, Buddhi D. Review on thermal energy storage with phase change materials and applications. Renew Sustain Energy Rev 2009;13:318–45.
[70] Kenisarin M, Mahkamov K. Solar energy storage using phase change materials. Renew Sustain Energy Rev 2007;11:1913–65.
[71] Tyagi VV, Buddhi D. PCM thermal storage in buildings: a state of art. Renew Sustain Energy Rev 2007;11:1146–66.
[72] Streicher W, Schultz JM, Solé C, Cabeza LF, Bony J, Citherlet S, et al. Final report of subtask C "phase change materials". Report C7—IEA SHC Task 32. International Energy Agency; 2008.
[73] Pinel P, Cruickshank CA, Beausoleil-Morrison I, Wills A. A review of available methods for seasonal storage of solar thermal energy in residential applications. Renew Sustain Energy Rev 2011;15:3341–59.
[74] Sharp MK, Loehrke RI. Stratified thermal storage in residential solar energy applications. J Energy 1979;3(2):106–13.
[75] Duffie JA, Beckman WA. Solar engineering of thermal processes. 3rd ed.. Madison, WI: John Wiley & Son; 2006.
[76] Altuntop N, Arslan M, Ozceyhan V, Kanoglu M. Effect of obstacles on thermal stratification in hot water storage tanks. Appl Therm Eng 2005;25(14–15): 2285–98.
[77] Crandall DM, Thacher EF. Segmented thermal storage. Sol Energy 2004;77: 435–40.
[78] Dincer I, Rosen MA. Thermal energy storage—systems and applications. New York: John Wiley & Son; 2002.
[79] Bertagnolio S, Stabat P, Caciolo M, Corgier D. Review of heat recovery and heat pumping solutions. IEA-ECBCS Annex 48 reversible air-conditioning. Paris: International Energy Agency; 2011.
[80] Aynur TN. Variable refrigerant flow systems: a review. Energy Build 2010;42: 1106–12.
[81] Masuda M, Wakahara K, Matsui K. Development of a multi-split system air conditioner for residential use. ASHRAE Trans 1991;97(2):127–31.
[82] Wu C, Xingxi Z, Shiming D. Development of control method and dynamic model for multi-evaporator air conditioners (MEAC). Energy Convers Manag 2005;46(3):451–65.
[83] Choi JM, Kim YC. Capacity modulation of an inverter-driven multi-air conditioner using electronic expansion valves. Energy 2003;28(2):141–55.
[84] Hu SC, Yang RH. Development and testing of a multi-type air conditioner without using AC inverters. Energy Convers Manag 2005;46(3):373–83.
[85] Zhou YP, Wu JY, Wang RZ, Shiochi S. Energy simulation in the variable refrigerant flow air-conditioning system under cooling conditions. Energy Build 2007;39(2):212–20.
[86] Calabrese C. Analisi dei sistemi di climatizzazione VRF nella ristrutturazione edilizia [Analysis of VRV energy systems in building retrofitting]. In: Proceedings of the AiCARR Conference Innovazione tecnologica nella climatizzazione degli edifici nuovi e ristrutturati [Technological innovation for air conditioning in new and renovated buildings]. Padova, Italy; June 16, 2011. p. 97–121 [Italian].
[87] Hepbasli A, Erbay Z, Icier F, Colak N, Hancioglu E. A review of gas engine driven heat pumps (GEHPs) for residential and industrial applications. Renew Sustain Energy Rev 2009;13:85–99.
[88] Flurschetz E. Use of heat pump in a municipal energy supply system. Elektrowarme International 1978;36:a164–7.
[89] Struck W, Willeitner E, Kok G. Generation of heat with diesel and gas-motor-heat-pumps. Klim Kaelte Ing 1978;6(7–8):279–84.
[90] Li MX, Ma YT, Wang JG, Kang F. Study of the multiple objective comprehensive evaluation for heating and air-conditioning systems. J Tianjin University 2003;36(3):311–5(Japanese).
[91] Zhao Y, Haibo Z, Zhiguang W. Technical and economic analysis of gas engine driven heat pump in China. Int J Glob Energy Issues 2003;20(3):223–32.
[92] Lian Z, Park S, Huang W, Baik Y, Yao Y. Conception of combination of gas-engine-driven heat pump and water-loop heat pump system. Int J Refrig 2005;28:810–9.
[93] Li YL, Zhang XS, Cai L. A novel parallel-type hybrid power gas engine-driven heat pump system. Int J Refrig 2007;30(7):1134–42.
[94] Srikhirin P, Aphornratana S, Chungpaibulpatana S. A review of absorption refrigeration technologies. Renew Sustain Energy Rev 2001;5(4):343–72.
[95] Pineau D, Rivière P, Stabat P, Hoang P, Archambault V. Performance analysis of heating systems for low energy houses. Energy Build 2013;65:45–54.
[96] Keil C, Plura S, Radspieler M, Schweigler C. Application of customised absorption heat pumps for utilization of low-grade heat sources. Appl Therm Eng 2008;28:2070–6.
[97] Busato F, Lazzarin RM, Noro M. Two years of recorded data for a multisource heat pump system: a performance analysis. Appl Therm Eng 2013;57:39–47.
[98] Hepbasli A, Kalinci Y. A review of heat pump water heating systems. Renew Sustain Energy Rev 2009;13:1211–29.
[99] Kim M, Kim MS, Chung JD. Transient thermal behavior of a water heater system driven by a heat pump. Int J Refrig 2004;27:415–21.
[100] Luo Q, Tang G, Liu Z, Wang J. A novel water heater integrating thermoelectric heat pump with separating thermosiphon. Appl Therm Eng 2005;25:2193–203.
[101] Pagani M. DHW production by means of heat pumps. Casa&Clima 2011;29:74–82 (Italian).
[102] Zhang J, Wang RZ, Wu JY. System optimization and experimental research on air source heat pump water heater. Appl Therm Eng 2007;27:1029–35.
[103] Biaou AL, Bernier MA. Achieving total domestic hot water production with renewable energy. Build Environ 2008;43:651–60.
[104] Neksa P, Rekstad H, Zakeri GR, Schiefloe PA. CO_2-heat pump water heater: characteristics, system design and experimental results. Int J Refrig 1998;21:172–9.
[105] Onovwiona HI, Ugursal VI. Residential cogeneration systems: review of the current technology. Renew Sustain Energy Rev 2006;10:389–431.
[106] Thilak Raj N, Iniyan S, Goic R. A review of renewable energy based cogeneration technologies. Renew Sustain Energy Rev 2011;15:3640–8.
[107] EDUCOGEN. The European educational tool on cogeneration. European Commission, SAVE programme; 2001.
[108] Macchi E, Campanari S, Silva P. La microcogenerazione a gas naturale [Natural gas-powered microcogeneration]. Milano: Polipress; 2005(Italian).
[109] Voorpools KR, D'haeseleer WD. The evaluation of small scale cogeneration for residential heating. Int J Energy Resour 2002;26:1175–90.
[110] Orlando JA. Cogeneration design guide. Atlanta, GA: ASHRAE; 1996.
[111] Resource Dynamics Corporation. Industrial applications for micropower: a market assessment. Washington, DC: Office of Industrial Technologies U.S. Department of Energy, Oak Ridge, TN: Oak Ridge National Laboratory; 1999.
[112] Energy Nexus Group. Technology characterization: reciprocating engines. Washington, DC: U.S. Environmental Protection Agency Climate Protection Partnership Division; 2002.
[113] Aspen Systems Corporation. Combined heat & power: a federal manager's resource guide. Washington, DC: U.S. Department of Energy Federal Energy Management Program; 2000.
[114] Andlauer B, Stabat P, Marchio D, Flament B. MCHP. Which future in low energy consumption houses? AiCARR J 2010;1(2):62–7(Italian).
[115] Sonntag RE, Borgnakke C, Van Wylen GJ. Fundamentals of thermodynamics. Hoboken, NJ: John Wiley & Sons Inc.; 2003.
[116] Bowman L. Small modular power development at External Power, LLC: residential and small commercial Stirling cogeneration systems. Orlando, USA: Fifth International Biomass Congress of the Americas; 2001.
[117] Urieli I, Berchowitz DM. Stirling cycle engine analysis. Bristol: Adam Hilger Ltd; 1984.
[118] MICROMAP. Mini and macro-CHP market assessment and development plan summary report. London: Faber Maunsell Ltd.; 2002.
[119] Moustafa S, Hoefler W, El-Mansy H, Kamal A, Jarrar D, Hoppman H, et al. Design specifications and application of a 100 kWc(700 kWth) cogeneration solar power plant. Sol Energy 1984;32:263–9.
[120] McDonald CF. A hybrid solar closed-cycle gas turbine combined heat and power plant concept to meet the continuous total energy needs of a small community. J Heat Recovery Syst 1986;6(5):399–419.
[121] Chakraborty S, Kramer B, Kroposki B. A review of power electronics interfaces for distributed energy systems towards achieving low-cost modular design. Renew Sustain Energy Rev 2009;13:2323–35.
[122] Göktun S. Solar powered cogeneration system for air conditioning and refrigeration. Energy 1999;24(11):971–7.
[123] Innova Technology Solution. Trinum solar co-generator system Overview; September 2010.
[124] US EPA. Environmental Technology Verification (ETV) program case studies. Demonstrating program outcomes. Cincinnati, OH: National Risk Management Research Laboratory Office of Research and Development U.S. Environmental Protection Agency; 2006.
[125] Bianchi M, Spina PR. Integrazione di sistemi cogenerativi innovativi di piccolissima taglia nelle reti di distribuzione dell'energia elettrica, termica e frigorifera [Integration of very small size innovative cogeneration systems within the electrical, thermal and cooling energy distribution systems]. Accordo di Programma Ministero dello Sviluppo Economico – ENEA; 2010 [Italian].
[126] Abu-Sharkh S, Arnold RJ, Kohler J, Li R, Markvart T, Ross JN, et al. Can microgrids make a major contribution to UK energy supply? Renew Sustain Energy Rev 2006;10:78–127.
[127] McDonald CF, Rodgers C. The ubiquitous personal turbine—a power vision for the 21st century. J Eng Gas Turbines Power 2002;124(4):835–44.
[128] Mazandarani A, Mahlia TMI, Chong WT, Moghavvemi M. Fuel consumption and emission prediction by Iranian power plants until 2025. Renew Sustain Energy Rev 2011;15(3):1575–92.
[129] Shekarchian M, Moghavvemi M, Mahlia TMI, Mazandarani A. A review on the pattern of electricity generation and emission in Malaysia from 1976 to 2008. Renew Sustain Energy Rev 2011;15(6):2629–42.
[130] Ismail MS, Moghavvemi M, Mahlia TMI. Current utilization of microturbines as a part of a hybrid system in distributed generation technology. Renew Sustain Energy Rev 2013;21:142–52.
[131] Hamilton S. The handbook of microturbine generators. Tulsa, OK: Penwell Books; 2003.
[132] Moore MJ, editor. Micro-turbine generators. Hoboken, NJ: John Wiley & Sons Inc;; 2005.
[133] Choudhury A, Chandra H, Arora A. Application of solid oxide fuel cell technology for power generation—a review. Renew Sustain Energy Rev 2013;20:430–42.
[134] Nazaroff WW, Boegel ML, Hollowell CD, Roseme GD. The use of mechanical ventilation with heat recovery for controlling radon and radondaughter concentrations in houses. Atmos Environ 1981;15:263–70.
[135] Liu D, Zhao FY, Tang GF. Active low-grade energy recovery potential for building energy conservation. Renew Sustain Energy Rev 2010;14:2736–47.
[136] Manz H, Huber H. Experimental and numerical study of a duct/heat exchanger unit for building ventilation. Energy Build 2000;32:189–96.

[137] Jokisalo J, Kurnitski J, Vuolle M, Torkki A. Performance of balanced ventilation with heat recovery in residential buildings in a cold climate. Int J Vent 2003;2(3):223–35.
[138] Mardiana-Idayu A, Riffat SB. Review on heat recovery technologies for building applications. Renew Sustain Energy Rev 2012;16:1241–55.
[139] Aparecida Silva C, Gendebien S, Hannay J, Hansens N, Lebrun J, Lengele M et al. Decentralized mechanical ventilation with heat recovery. In: Proceedings of the 32nd AIVC conference. Bruxelles, Belgium; October 12–13, 2011.
[140] Masy G, Lebrun J, Gendebien S, Hansen N, Lengele M, Prieels L. Performances of DAHT connected to building airthightness and indoor hygrothermal climate. In: Proceedings of the 32nd AIVC conference. Bruxelles, Belgium; October 12–13, 2011.
[141] Morelli M, Rønby L, Mikkelsen SE, Minzari MG, Kildemoes T, Tommerup HM. Energy retrofitting of a typical old Danish multi-family building to a "nearly-zero" energy building based on experiences from a test apartment. Energy Build 2012;54:395–406.
[142] Italian National Standards Body. UNI EN 7129:2008. Gas plants for domestic and similar uses supplied by network – design and installation [Italian].
[143] The European Commission. Draft working document ventilation units [Internet]; October 10, 2012. Available from: 〈http://ec.europa.eu/enterprise/policies/sustainable-business/ecodesign/product-groups/airco-vent/files/swd_ventilation_en.pdf〉.
[144] Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products (recast); October 31, 2009.
[145] Benedici G. [More stringent requirements on domestic ventilation]. Casa&Clima 2011;6(31):58–64 (Italian).
[146] Bo M, Bo G, Mancin M. Il recupero termodinamico sull'aria espulsa effettuato mediante pompe di calore invertibili [Thermodynamic heat recovery on exhaust air by means of reversible heat pumps]. Proceedings of the AiCARR Conference Rispondere alla crisi energetica con l'integrazione edificio-impianto: la pompa di calore invertibile [Answering to the energy crisis with the building-plant integration: the reversible heat pump]. Bologna, Italy; Oct 28, 2010 [Italian].
[147] Feist W, Schnieders J, Dorer V, Haas A. Re-inventing air heating: convenient and comfortable within the frame of the Passive House concept. Energy Build 2005;37:1186–203.
[148] Feist W, Peper S, Görg M. CEPHEUS-Projectinformation no. 36. Final technical report. Hanover: Enercity; July 2001.
[149] Feist W, Pfluger R, Kaufmann B, Schneiders J, Kah O. Passive house planning package. Darmstadt: The Passive House Institute; 2007.
[150] Feist W. Recommendation for inside air humidity in winter, in homes with ventilation systems, particularly passive homes. Darmstadt: The Passive House Institute; 2000.
[151] Dimitroulopoulou C. Ventilation in European dwellings: a review. Build Environ 2012;47:109–25.
[152] Becchio C, Corgnati SP, Fabrizio E, Monetti V. The cost optimal methodology applied to an existing office in Italy. REHVA Eur HVAC Journal 2013;50(5):18–22.
[153] Lewis M. Integrated design for sustainable buildings. ASHRAE J 2004;46(9):S22–S30.
[154] Fabrizio E, Filippi M, Virgone J. Trade-off between environmental and economic objectives in the optimization of multi-energy systems. Buildi Simul: Int J 2009;2(1):29–40.